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A STUDY TO DETERMINE THE OPTIMUM METHOD FOR FORMING CLOSED-RIBBED PLATE TO CYLINDRICAL AND SPHERICAL SHAPES

FINAL REPORT

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INTRODUCTION

This report has been prepared for the National Aeronautics and Space Administration in response to Order No. T. P. 3-82403 for a study to determine the optimum method for forming closed-ribbed plate to cylindrical and spherical shapes.

The report covers present methods, techniques, and equipment now employed in production of sheet metal parts, pointing out the need for adaptation of these methods and equipment for production of large, complex missile components. Present methods do not provide for forming these heavy machined sections to the close tolerances required. In reviewing existent published information on forming it has been found that it covers only a limited range mostly lighter gage material, and confirms that each fabrication, as a general rule, establishes empirical rules for forming processes based on experience and plant facilities.

Information presented in the report covers the various forming methods; analytical derivations and equations pertinent to stresses encountered by employing the various methods; test data and photographic documentation showing heavy machined sections formed to contour; and recommendations and conclusions.

1/ FORMING CONCEPTS

1.1 GENERAL

When considering the forming of closed-rib stiffened sections to cylindrical or hemispherical shapes, the following concepts or methods appear to be applicable depending upon the final part contour desired.

Roll forming

Press forming

Stretch forming

Shot peen forming

High energy forming

Age or creep forming

A brief description of each of these methods is presented and where applicable the forming operation required is classified into one of the general basic types, such as bending, stretching, shrinking, or combinations thereof.

1.2 ROLL FORMING

This method utilizes bending rolls which usually conforms to the 3-point bending or cantilever bending principle. In either case the forming action is one of bending and can form sections into singly curved, smoothly contoured parts.

The bending of sections is based on beam bending formula, assuming the neutral axis passes through the centroid of the section.

Closed-rib sections could be contoured to cylindrical shapes utilizing this method. The tendency to wrinkle or buckle would be controlled by adding support to the ribs with flexible or cast-in inserts. Springback would be compensated for by proper setting, rerolling, or overbending.

The type of failures generally encountered in roll forming is cracking in the radial planes at the outside of the curvature and wrinkling or collapse at the inside of the curvature.

1.3 PRESS FORMING

Presses are machines which consist of a frame supporting a bed and a ram, a power source and some mechanism to move the ram at right angles and in line with the bed. This method would utilize press dies or mating dies to curve the sections to the contour desired. Sections formed by this method are subject to cracking on the convex surface and wrinkling on the concave surface just as in other bending operations.

1.4 STRETCH FORMING

The operation of stretch wrapping consists of gripping the section and applying a load sufficient to stress the material to its elastic limit and then wrapping the material around the stretch block after which the load is increased a small amount to give the material a final set.

Sections formed by this method are subject to failure by fracturing at locations of maximum stretch and buckling during wrapping. This method could be utilized for contouring closed-rib sections to cylindrical and shallow hemispherical shapes.

One advantage of this process is the relatively low amount of springback, therefore the better predictability of successful forming.

1.5 SHOT PEEN FORMING

The shot peening process is accomplished by propelling shot of uniform round shape and size at controlled velocity against a workpiece. When this process is applied to only one surface of the metal, the object will be bent with the convex surface on the peened side. Curvature results from the fact that a compression layer is created on the bombarded surface. Intensity is the measure of the effect of a blast of shot on a part and it is dependent upon the diameter, hardness, angle of impact, and velocity of the shot. By carefully controlling the intensity over one surface the part can be formed to contour. A very desirable feature of peen forming is the fact that no tooling is required other than the peening facility.

1.6 HIGH ENERGY FORMING

High energy forming, more commonly known as explosive forming, is basically a method of applying high pressure at extremely high speed. The energy release is obtained from dynamite, black powder, gases or electric spark; with the subsequent transfer of the energy to the blank taking place by the shock wave directly or transmitted by various mediums such as gas, water, or rubber. Only a female die is required, and depending on the method being used, the die material can be wood, plaster, plastic, or tool steels. A vacuum beneath the workpiece is essential in order that the piece may reach the die and prevent burning of the surfaces. Presently, explosive forming offers the advantage of being able to form large sections because of the availability of a large source of energy. However, further research is still necessary for the development of fundamentals. For example, the control of forming velocity and pressure profile to increase the elongation of the material. Some other variables are the size, composition and shape of charge, location of the charge and distance from the blank. In addition, an evaluation of transfer mediums and development of filler materials to eliminate the embossing effect produced through canning or bulging of the pockets must be considered.

At the present state-of-the-art the use of this concept on closed-rib panels would require many hours of trial and error in establishing a technique for producing a specific part.

1.7 AGE OR CREEP FORMING

Those processes which utilize dies or fixtures, pressure or heat, to form a part to desired contour are grouped under this heading. This method involves the contouring of the section at room temperature in a jig or fixture, then heating the part to about the aging temperature of the alloy. In one case, the age-hardened part is contoured at room temperature and then heated for a specific time and temperature, while in the other case, the fixtured part is contoured at room temperature in the solution heated condition and then is held at a constant time and temperature during the controlled age cycle.

Although the stresses induced by fixturing or jigging the part at room temperature are below the yield strength of the material, at the elevated temperature these stresses are now above the yield strength, thereby producing plastic flow which remains as permanent deformation on cooling to room temperature. Since the forming action takes place by the same mode in each method, in both cases the part must be overcontoured to compensate for springback. The springback allowance to be incorporated into the fixtures would be developed empirically for each method. Also in the case of creep forming of aged condition material, temperature and time cycle to give the optimum properties would have to be established by laboratory tests.

Basically this method involves either bending or stretching the part to contour prior to heating. Therefore, the limits and forming variables of bending and/or stretching principles will apply.

1.8 FILLER MATERIALS

Depending on the degree of contouring and the relative dimensions of the section being formed, it is expected that there would be some tendency for closed-rib shapes to collapse as forming forces are applied. Therefore, the use of various fillers consisting of wood, fibre, plastic, metallic snakes, or low melting paint alloys would be necessary. The filler's purpose is to stabilize the ribs to prevent buckling and to distribute applied bending forces to preclude local bearing failure. The following factors should be used as a guide in the selection of a specific filler materials for the best overall results:

(a) They should conform to the shape of the section.

(b) They should be resilient.

(c) They should be easily removed.

(d) They should be reusable.

Based on the factors listed, the low melting paint alloys appear to be the best choice. However, our experience with both plastic and low melting-point alloy fillers in roll forming operations showed that the plastic fillers were superior. When Cerro-bend was used during roll forming of a similar 90-degree waffle pattern panel, the ribs cracked at the tangency point of the fillet radius. This was due to the relative ease with which progressive flow of the Cerro-bend took place in front of the forming roll, thus causing a local increase in the force exerted against one side of the transverse rib. Plastic fillers, being resilient, allow a more fluid flow and exert pressure in all planes. In stretch forming operations the low melting point alloys should perform satisfactory because of the uniform load distribution inherent in this method of forming.

The thermoset casting resins offer some versatility because the necessary flexibility can be tailored to fit the forming conditions. Plastic fillers can be satisfactorily used in stretch forming and should be compounded for maximum hardness for greater stiffness, combined with some flexibility. A series of lateral cuts extending from one edge of the filler to 75% of its thickness can be employed to obtain necessary flexibility. These cuts lessen the circumferential stiffness while maintaining the lateral stiffness. By using a casting-type thermosetting plastic system, the cuts or grooves can be produced in the mold.

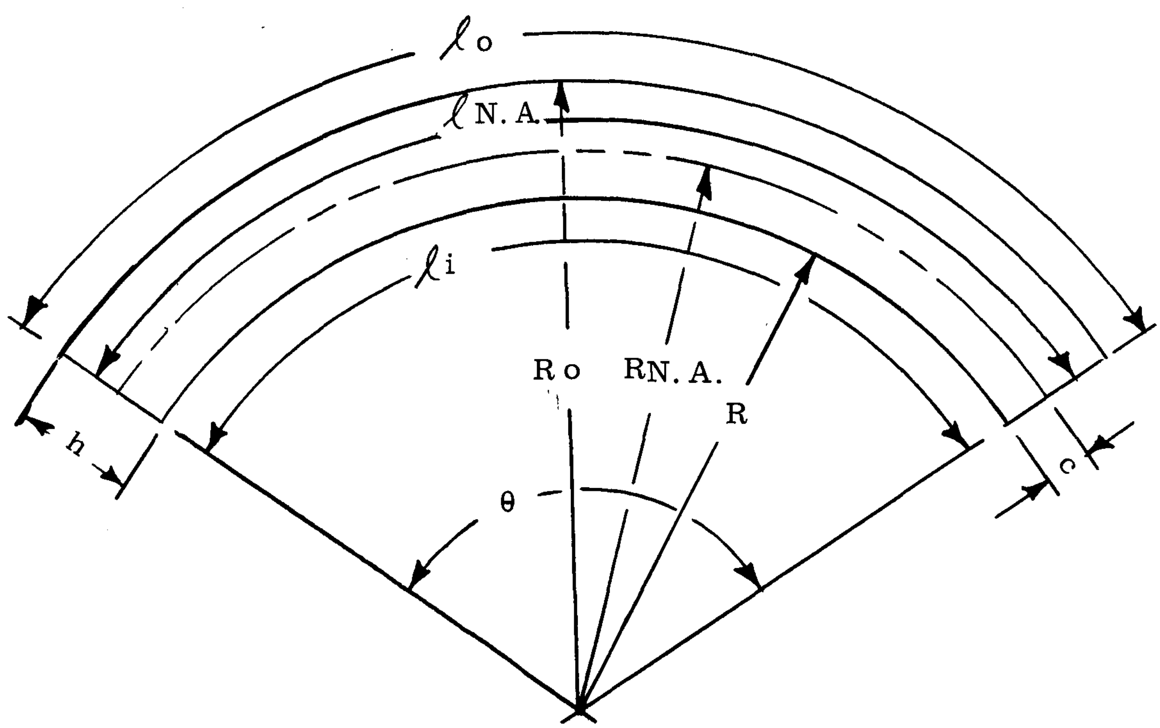
2/ ANALYTICAL DERIVATIONS

2.1 ANALYTICAL STUDY

The following analytical study primarily involves three basic methods of forming, namely: stretch forming, roll forming, and brake forming. As in all types of forming, the primary parameter for analysis is strain. Therefore, all forming characteristics must be thought of in terms of strain. This is necessary in that stress is not a linear function of elongation within the plastic range (elastic only). Strain can then be easily correlated to stress and modulus of elasticity with the utilization of definitive stress-strain curves of the appropriate material.

The first step in the derivation of forming predictability is the evaluation of strain characteristics related to bending. The process of bending is common to the three forming concepts mentioned above.

When a shape is subjected to bending, stretch of the outer fibers and shrinkage of the inner fibers results.



The original length, ℓ, is assumed to remain constant along the neutral axis, N. A., but the outside length, ℓ_o, increases and the inside length, ℓ_i, decreases as the section is bent to the radius R.

Original length, ℓ, $= \ell_{N.A.}$

From geometry:

$$\theta = \frac{\ell_{N.A.}}{R_{N.A.}} \qquad \ell_{N.A.} = R_{N.A.}\,\theta$$

where

$$R_{N.A.} = R + c$$

The strain resulting on the outside surface, ϵ_o, is derived as follows:

$$\epsilon_o = \frac{\ell_o \ell_{N.A.}}{\ell_{N.A.}}$$

It is pointed out that strain is the elongation per unit length (one inch) and not the total elongation.

$$\epsilon_o = \frac{R_o\theta - R_{N.A.}\theta}{R_{N.A.}\theta}$$

$$R_o = R + h$$

$$R_{N.A.} = R + c$$

then by substitution,

$$\epsilon_o = \frac{\theta\,(R+h) - \theta\,(R+c)}{\theta\,(R+c)}$$

$$= \frac{(R+h) - (R+c)}{(R+c)}$$

$$= \frac{h-c}{R+c} \qquad (1)$$

The strain resulting on the inner surface, ϵ_i, is derived as follows:

$$\epsilon_i = \frac{\ell_{N.A.} - \ell_i}{\ell_{N.A.}}$$

$$= \frac{R_{N.A.}\,\theta - R\theta}{R_{N.A.}\,\theta}$$

$$= \frac{\theta\,(R + c) - R\theta}{\theta\,(R + c)}$$

$$= \frac{(R + c) - R}{R + c}$$

$$= \frac{c}{R + c} \qquad (2)$$

It should be noted that formula (2) is negative (contraction).

2.2 STRETCH WRAP FORMING

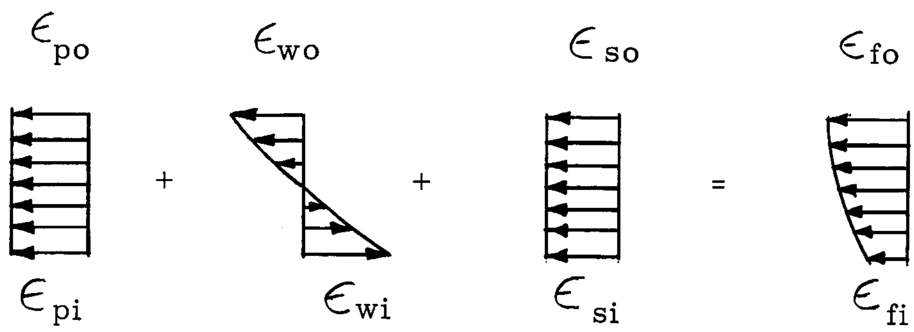
In the process of stretch forming three steps must take place. The first is stretching, where the shape is subjected to an axial tensile load with a stress level at the yield point. The second step is the wrapping operation. This is performed while maintaining the same initial load. During wrapping the effective neutral axis shifts toward the inner edge of the part. The final step is the application of an additional axial tensile load which performs the function of "setting" the part to the die contour.

The initial stretch strains are defined for the outer surface as ϵ_{po} and for the inner surface as ϵ_{pi}.

The wrapping strains are defined as ϵ_{wo} for the outer surface and ϵ_{wi} for the inner surface, and are as given by equations (1) and (2).

The setting strains are defined as ϵ_{so} for the outer surface and ϵ_{si} for the inner surface.

ϵ_{fo} and ϵ_{fi}, the final resultant strains at the outer and inner surface, respectively, are attained by combining the three steps shown.



preload + wrap + set = final

$$\epsilon_{fo} = \epsilon_{po} + \epsilon_{wo} + \epsilon_{so} \tag{3}$$

$$\epsilon_{fi} = \epsilon_{pi} + \epsilon_{wi} + \epsilon_{si} \tag{4}$$

Each individual strain must be assigned a limit or range to avoid failure, therefore

$$\epsilon_{fo} \leqq \epsilon_{tu} \tag{5}$$

where ϵ_{tu} is the ultimate allowable tension strain

$$\epsilon_{fi} \leqq \epsilon_{ty} \leqq \epsilon_{tu} \tag{6}$$

where ϵ_{ty} is the strain corresponding to the tension yield point.

These limits preclude fracture of the part and provide final tension stresses within the plastic range to avoid significant residual stresses which create spring back.

$$\epsilon_{po} = \epsilon_{pi} = \epsilon_{ty} \tag{7}$$

This stress level places the part initially at the plastic range and allows for a greater induced compression stress on the inner surface from wrapping. Effectively, the neutral axis is shifted inward.

To avoid premature failure of the part during wrapping, the following limits must be set.

$$\epsilon_{po} + \epsilon_{wo} \leq \epsilon_{tu} \tag{8}$$

and

$$\epsilon_{pi} \qquad \epsilon_{wi} \leq \epsilon_{ccr} \tag{9}$$

where ϵ_{ccr} is the critical compressive strain of the part below the neutral axis. This may range from a buckling limit below the compressive yield point to the ultimate compressive strength of the material depending on the part configuration.

For configurations having flanges or webs on concave side of part, it must be determined if buckling is critical (where $F_{cr} < F_{cu}$). This may be accomplished with the buckling formula

$$F_{ccr} = KE^1 \left(\frac{t}{b}\right)^2 \tag{10}$$

F_{ccr} = critical buckling stress

E^1 = $\sqrt{E\ E_t}$ (effective modulus)

E = compressive modulus

E_t = tangent modulus

a = length of flange or web

b = effective height of flange or width of web in compression. (As an approximation use distance from inner edge to neutral axis.)

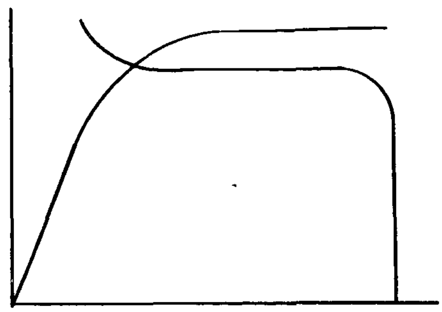
K = geometrical constant, a function of a/b and edge support.

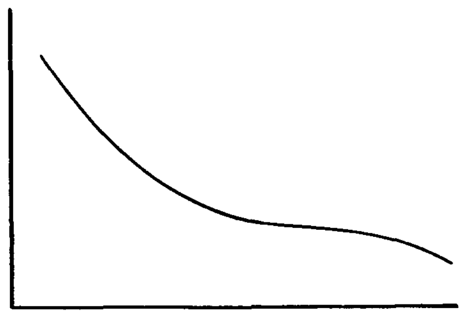
t = thickness of flange or web.

Since strain is a function of stress

$$\epsilon = f(F)$$

the critical compressive strain (ϵ_{ccr}) for any value of b/t can be arrived at with the usage of the appropriate stress-strain and tangent modulus curves.





This strain ϵ_{ccr} therefore becomes the limiting compressive strain. It must be equal to or less than the ultimate compressive strain.

In this study for the ribs, a K value of 1.10 is used. This reflects a panel with three sides clamped and one unloaded edge free.

Equation (3) becomes, by substitution using equations (1), (5), and (7).

$$\epsilon_{fo} = \epsilon_{ty} + \frac{h-c}{R+c} + \epsilon_{so} \leqq \epsilon_{tu} \tag{11}$$

and equation (4) becomes, by substitution using equations (2), (6), and (7).

$$\epsilon_{fi} = \epsilon_{ty} - \frac{c}{R+c} + \epsilon_{si} \geqq \epsilon_{ty} \tag{12}$$

from equation (3) and equations (5), (7), and (1).

$$\epsilon_{so} = \epsilon_{fo} - \epsilon_{po} - \epsilon_{wo}$$

$$= \epsilon_{tu} - \epsilon_{ty} - \frac{h-c}{R+c} \tag{13}$$

$$\epsilon_{si} = \epsilon_{so}$$

substituting into formula (12)

$$\epsilon_{ty} = \epsilon_{ty} - \frac{c}{R+c} + \epsilon_{tu} - \epsilon_{ty} - \frac{h-c}{R+c}$$

$$\frac{h-c}{R+c} + \frac{c}{R+c} = \epsilon_{tu} - \epsilon_{ty}$$

$$\frac{h}{R+c} = \epsilon_{tu} - \epsilon_{ty}$$

$$R = \frac{h-c\ (\epsilon_{tu} - \epsilon_{ty})}{\epsilon_{tu} - \epsilon_{ty}} \qquad (14)$$

Equation (14) becomes the limiting equation to provide for plasticity at the inner surface of the part to assure "set" and to preclude tension failure of the part while the set is applied. This is the tension criteria formula.

From equation (9) and subsequent explanation

$$\epsilon_{ccr} = \epsilon_{pi} - \epsilon_{wi}$$

$$\epsilon_{ccr} = \epsilon_{ty} - \frac{c}{R+c}$$

$$\frac{c}{R+c} = \epsilon_{ty} - \epsilon_{ccr}$$

$$R = \frac{c\,(1-\epsilon_{ty} + \epsilon_{ccR})}{\epsilon_{ty} - \epsilon_{ccR}} \qquad (15)$$

Equation (15) becomes the limiting equation to preclude compression failure at the inner edge during wrapping. NOTE: ϵ_{ccr} is numerically negative. This becomes the compression criteria formula.

A check of the actual strains encountered in a part for any arbitrary or minimum calculated radius may be made as follows:

1. The strain at the inner fiber resulting from wrapping is

$$\epsilon_c = \epsilon_{pi} - \epsilon_{wi} \quad \text{(equation 9)}$$

and therefore

$$\epsilon_c = \epsilon_{ty} - \frac{c}{R+c}$$

This will be equal to or less than the critical compressive strain.

2. The strain at the outer fiber resulting from wrapping is

$$\epsilon_t = \epsilon_{po} + \epsilon_{wo} \quad \text{(equation 8)}$$

and therefore

$$\epsilon_t = \epsilon_{ty} + \frac{h-c}{R+c}$$

This will be greater than the tensile yield strain and less than the ultimate tensile strain.

3. The strain at the inner fiber resulting from the "set" operation is

$$\epsilon_{fi} = \epsilon_{pi} - \epsilon_{wi} + \epsilon_{si} \quad \text{(equation 4)}$$

and therefore the required set strain (since $\epsilon_{fi} = \epsilon_{ty}$) will be

$$\epsilon_{si} = \frac{c}{R+c}$$

4. The strain at the outer fiber resulting from the set operation is

$$\epsilon_{fo} = \epsilon_{po} + \epsilon_{wo} + \epsilon_{so} \text{ (equation 3)}$$

therefore, since $\epsilon_{so} = \epsilon_{si}$

$$\epsilon_{fo} = \epsilon_{ty} + \frac{h-c}{R+c} + \frac{c}{R+c}$$

and

$$\epsilon_{fo} = \epsilon_{ty} + \frac{h}{R+c}$$

this will be equal to or less than the ultimate tensile strain.

It should be noted that the theory of biaxial and triaxial strains is not taken into account. Preliminary investigation has shown that these strains are not of the same magnitude as the above derived primary strains. For convenience they are ignored and the above predictability limits should be within practical tolerance.

2.3 ROLL AND BRAKE FORMING

In the process of either roll or brake forming only one significant operation occurs: this is bending. In the theoretical study of forming limits, secondary effects such as roll pressure, brake pressure, and axial forces induced by the rolls are assumed to be of a lesser order than bending and are therefore omitted from this study.

The strain on the outer fiber, as defined in equation (1), is

$$\epsilon_o = \frac{h-c}{R+c}$$

where

$$\epsilon_o \leqq \epsilon_{tu}$$

therefore

$$\frac{h-c}{R+c} = \epsilon_{tu}$$

$$R = \frac{h-c\ (1+\epsilon_{tu})}{\epsilon_{tu}} \qquad (16)$$

Equation (16) becomes the limiting equation to preclude tension failure during bending of the part.

The strain on the inner fiber, as defined in equation (2), is

$$\epsilon_i = \frac{c}{R+c}$$

where

$$\epsilon_i = \epsilon_{ccr}$$

ϵ_{ccr} is derived as presented in section for stretch wrapping (reference pages 2-5 and 2-6).

$$\frac{c}{R+c} = \epsilon_{ccr}$$

$$R = \frac{C(1 - \epsilon_{ccr})}{\epsilon_{ccr}} \qquad (17)$$

Equation (17) becomes the limiting equation to preclude compression failure during bending of the part.

The two equations, (16) and (17), are the limits for actual bending of the part and do not reflect a predicted formed radius. This is true because of considerable spring-back existent in roll and brake forming.

2.4 SUMMARY

The basic equations, for determining minimum forming radii for the closed rib cylindrical panel sections, are listed below. For each forming method one of the two (either tension or compression) will be critical.

2.4.1 STRETCH WRAP FORMING

Tension:

$$R_{(min)} = \frac{h-c\,(\epsilon_{tu} - \epsilon_{ty})}{\epsilon_{tu} - \epsilon_{ty}} \tag{14}$$

Compression:

$$R_{(min)} = \frac{c(1 - \epsilon_{ty} + \epsilon_{ccr})}{\epsilon_{ty} - \epsilon_{ccr}} \tag{15}$$

2.4.2 ROLL AND BRAKE FORMING

Tension:

$$R_{(min)} = \frac{h-c\,(1 + \epsilon_{tu})}{\epsilon_{tu}} \tag{16}$$

Compression:

$$R_{(min)} = \frac{c(1 - \epsilon_{ccr})}{\epsilon_{ccr}} \tag{17}$$

3/ PREDICTING LIMITS

3.1 GENERAL

Charts are presented for determining the forming limits of varying configurations at ribbed patterns. These charts relate to the three forming methods studied in the preceding section.

The geometrical parameters were chosen so as to include the range of configurations intended to be studied. The charts also relate to the three aluminum alloys: 2014-T6, 2219-T87, and 7039-T6. The mechanical properties are typical values.

3.2 CHART CONSTRUCTION

The stress-strain curves, tangent modulus, and effective modulus curves (figures 1-3) were constructed from tensile and compression data. As stated in Section 2, the effective modulus, E^1, is an empirical modulus and is equal to $\sqrt{E_t E}$.

The compression buckling curves (figures 4-6) were constructed from the buckling formula, $F_{ccr} = KE^1(t/b)^2$ and figures 1-3 correlating stress to strain.

The stretch wrap forming curves for tension (figures 7-9) utilize equation (14), Section 2, and strain data from figures 1-3. The stretch wrap forming curves for compression (figures 10-12) utilize equation (15), Section 2, strain data from figures 1-3 and strain data from figures 4-6.

The roll and brake forming curves for tension (figures 13-15) utilize equation (16), Section 2, and strain data from figures 1-3. The roll and brake forming curves for compression (figures 16-18) utilize equation (17), Section 2, strain data from figures 4-6 and strain data from figures 1-3.

The ultimate allowable strain, ϵ_{tu}, is arbitrarily factored by .9 wherever used. This is for assurance reasons and is conservative.

3.3 PROCEDURE

To determine the minimum forming radius for any given geometrical shape, first calculate the section properties "moment of inertia" and "area." Moment of inertia is then used to determine dimension "C" the distance from the inner fiber to the neutral axis. The area is used in stretch wrapping to determine machine capability of stretching a part to a specified strain.

The next step is to enter the appropriate charts to determine a minimum value of "R" for tension and a minimum value of "R" for compression. The largest value of "R" then becomes the critical value; the least radius to which the part can be formed.

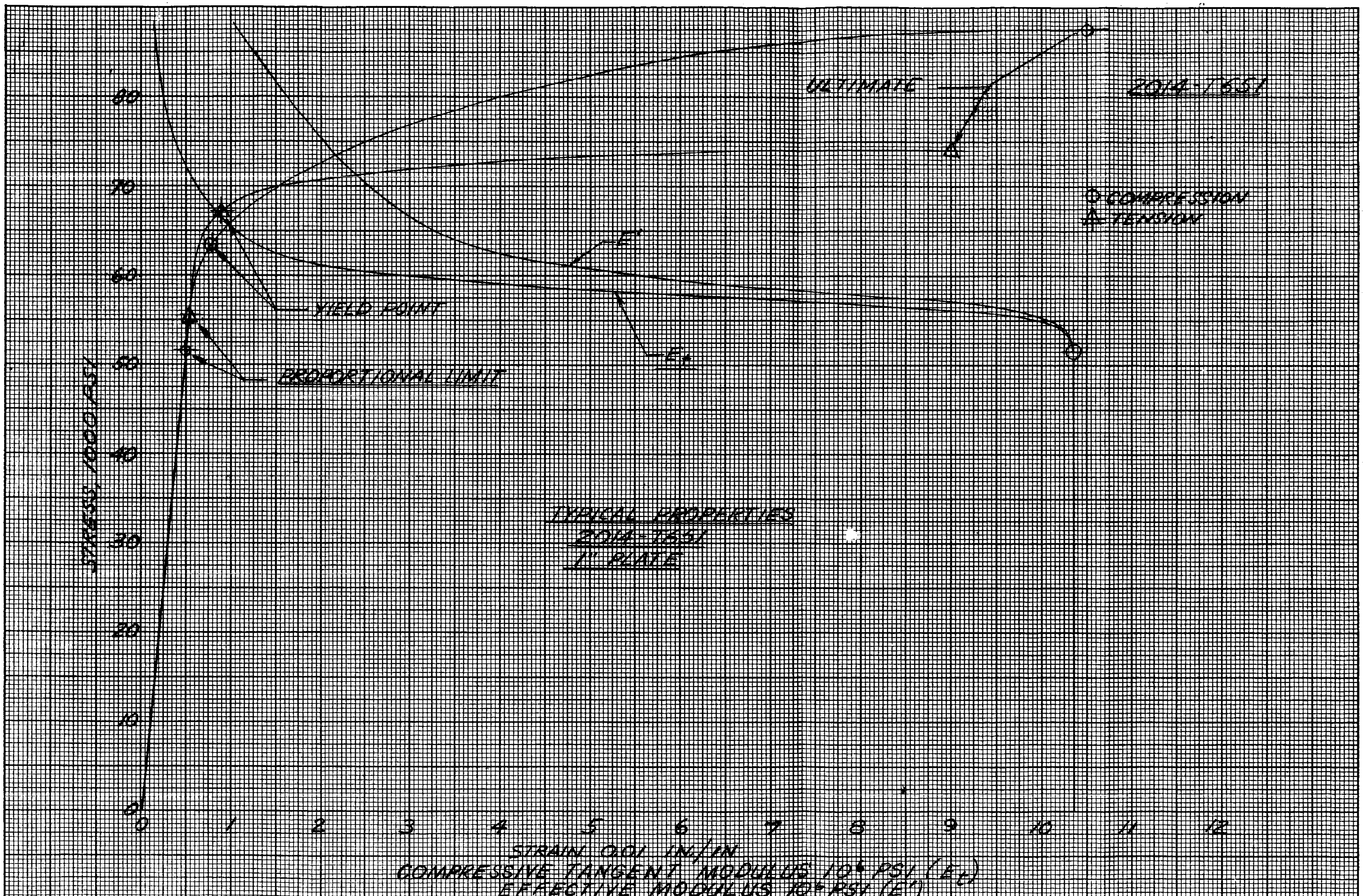
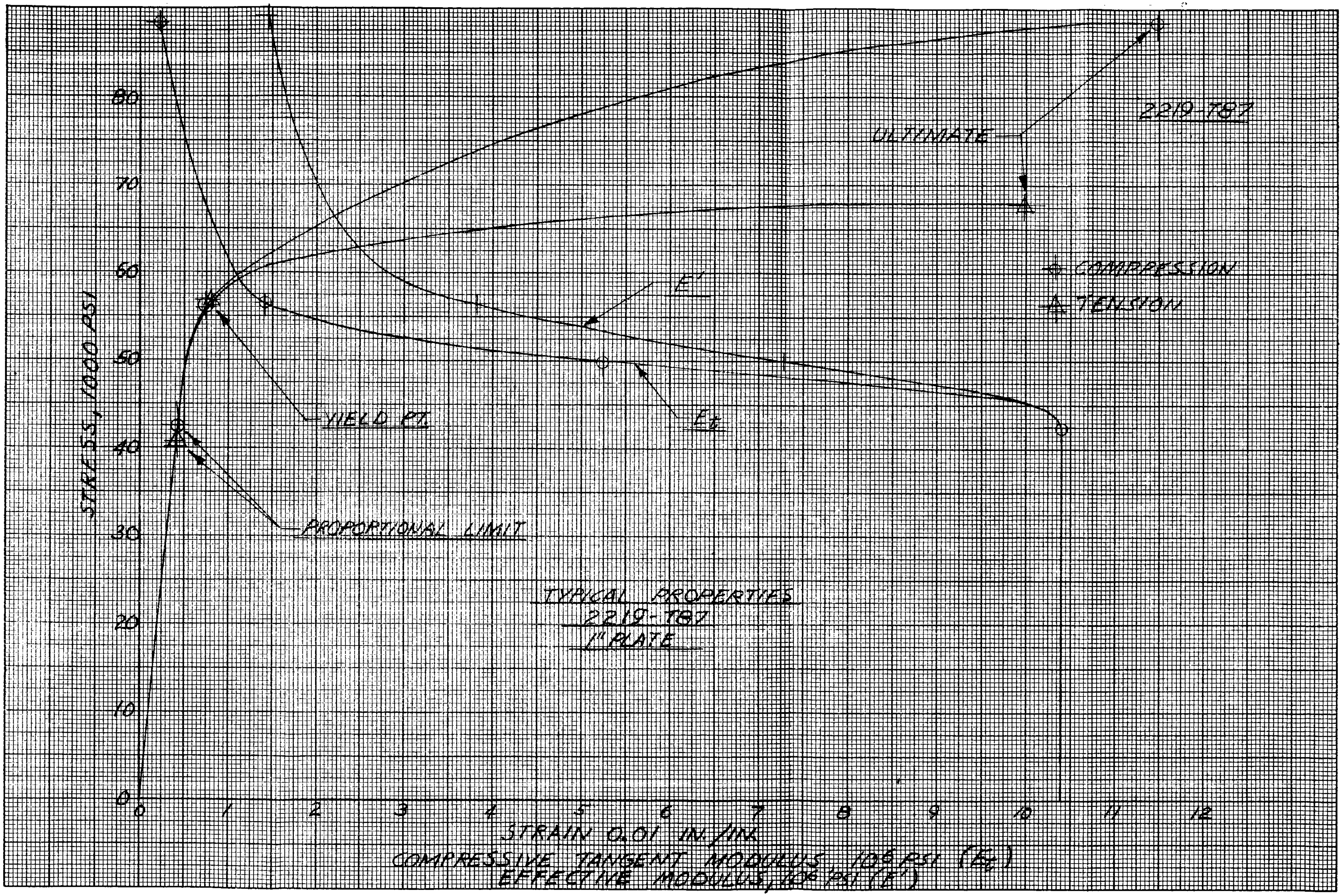
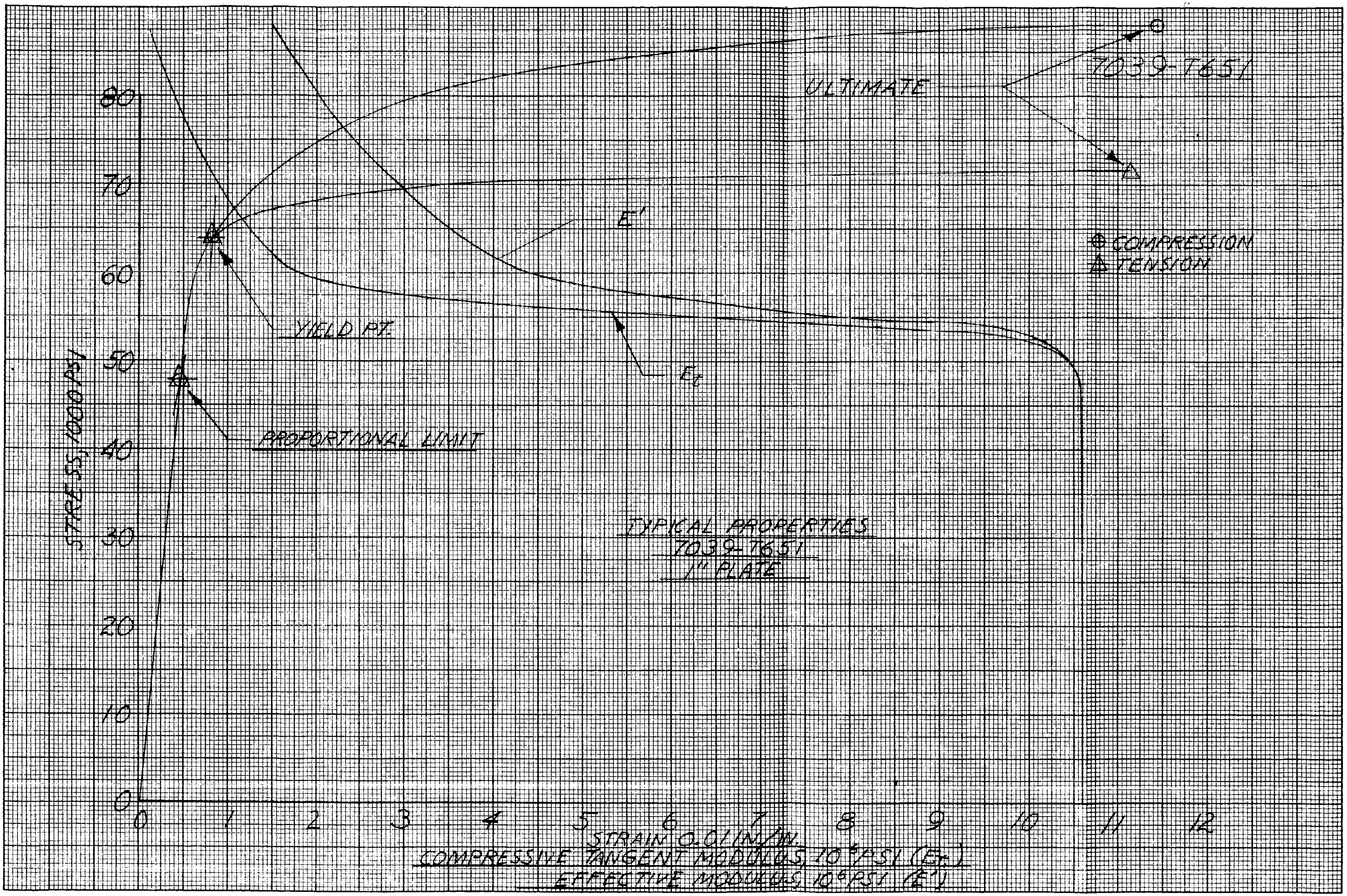

2014-T651
ULTIMATE
COMPRESSION
TENSION
E'
YIELD POINT
E_t
PROPORTIONAL LIMIT
STRESS, 1000 PSI
TYPICAL PROPERTIES
2014-T651
1" PLATE
STRAIN .001 IN/IN
COMPRESSIVE TANGENT MODULUS 10^6 PSI (E_t)
EFFECTIVE MODULUS 10^6 PSI (E')

FIGURE 1



2219-T87
ULTIMATE
COMPRESSION
TENSION
E'
E_t
YIELD PT.
PROPORTIONAL LIMIT
TYPICAL PROPERTIES
2219-T87
1" PLATE
STRESS, 1000 PSI
0
10
20
30
40
50
60
70
80
0
1
2
3
4
5
6
7
8
9
10
11
12
STRAIN 0.01 IN./IN.
COMPRESSIVE TANGENT MODULUS, 10^6 PSI (E_t)
EFFECTIVE MODULUS, 10^6 PSI (E')

FIGURE 2



STRESS, 1000 PSI
80
70
60
50
40
30
20
10
0
0
1
2
3
4
5
6
7
8
9
10
11
12
STRAIN 0.01 IN/IN
COMPRESSIVE TANGENT MODULUS, 10^6 PSI (E_t)
EFFECTIVE MODULUS 10^6 PSI (E')
ULTIMATE
7039-T651
COMPRESSION
TENSION
E'
E_t
YIELD PT.
PROPORTIONAL LIMIT
TYPICAL PROPERTIES
7039-T651
1" PLATE

FIGURE 3

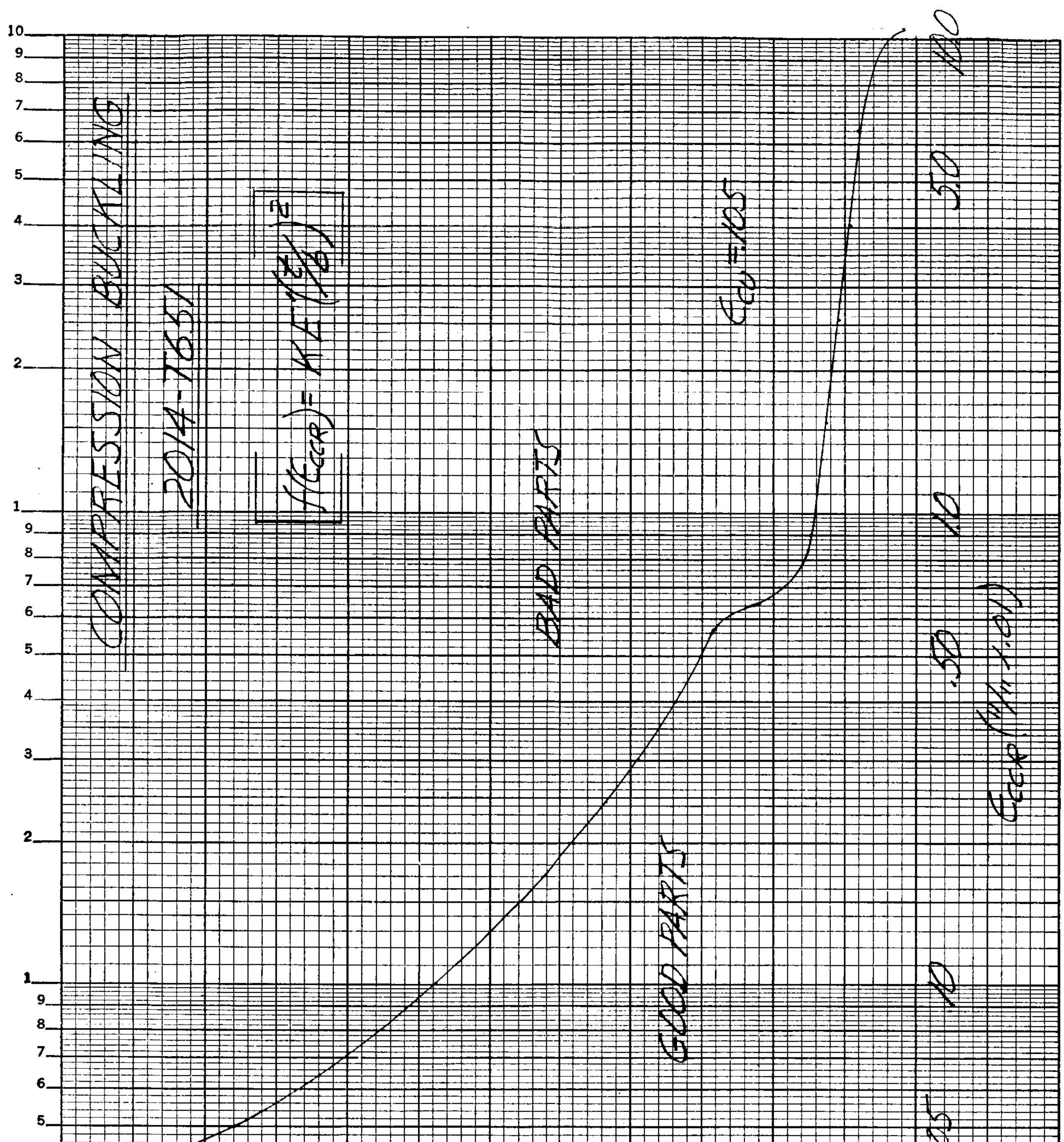

COMPRESSION BUCKLING
2014-T651
BAD PARTS
GOOD PARTS
50
40
30
20
10
0
b/t

FIGURE 4

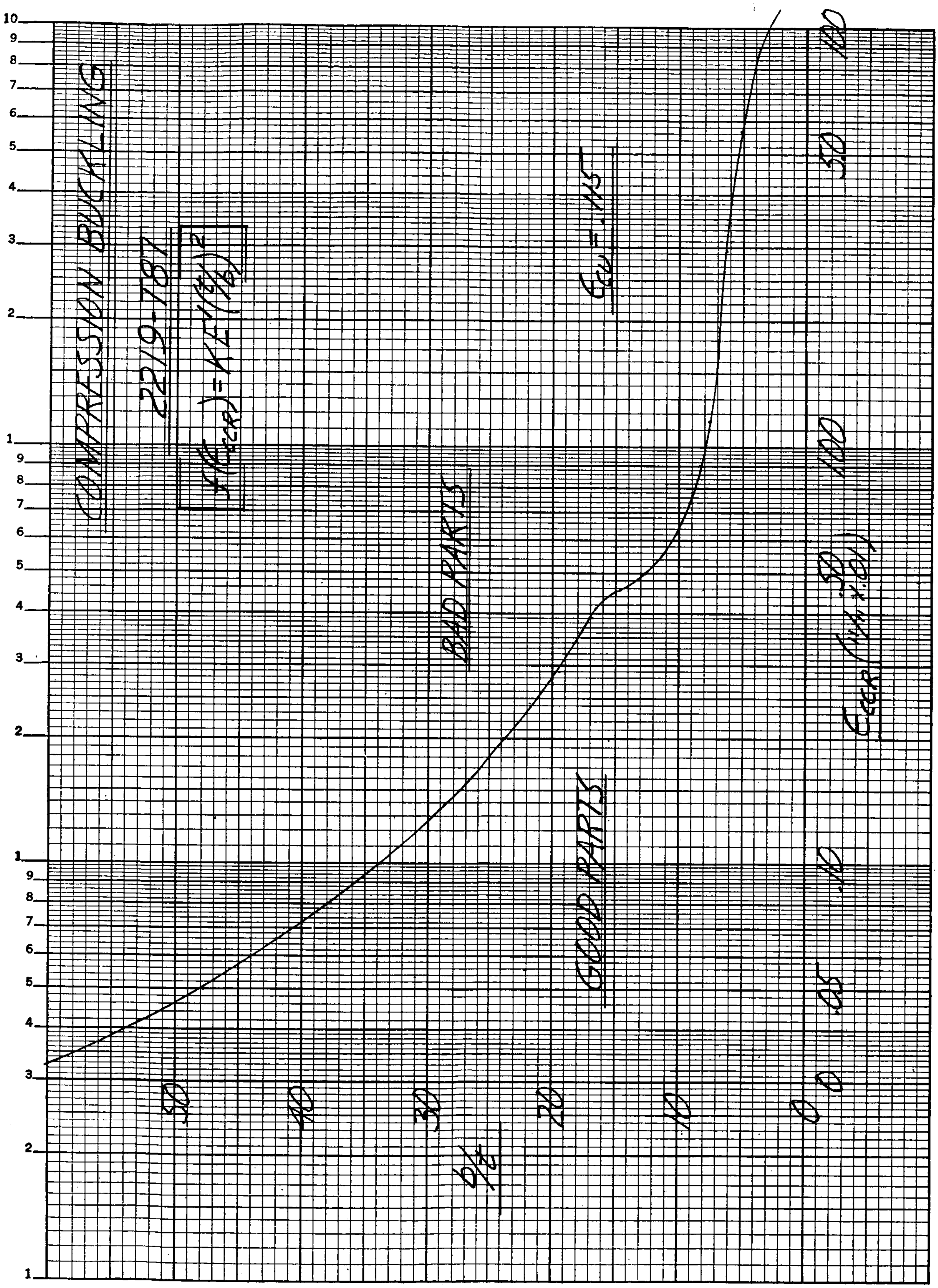


FIGURE 5

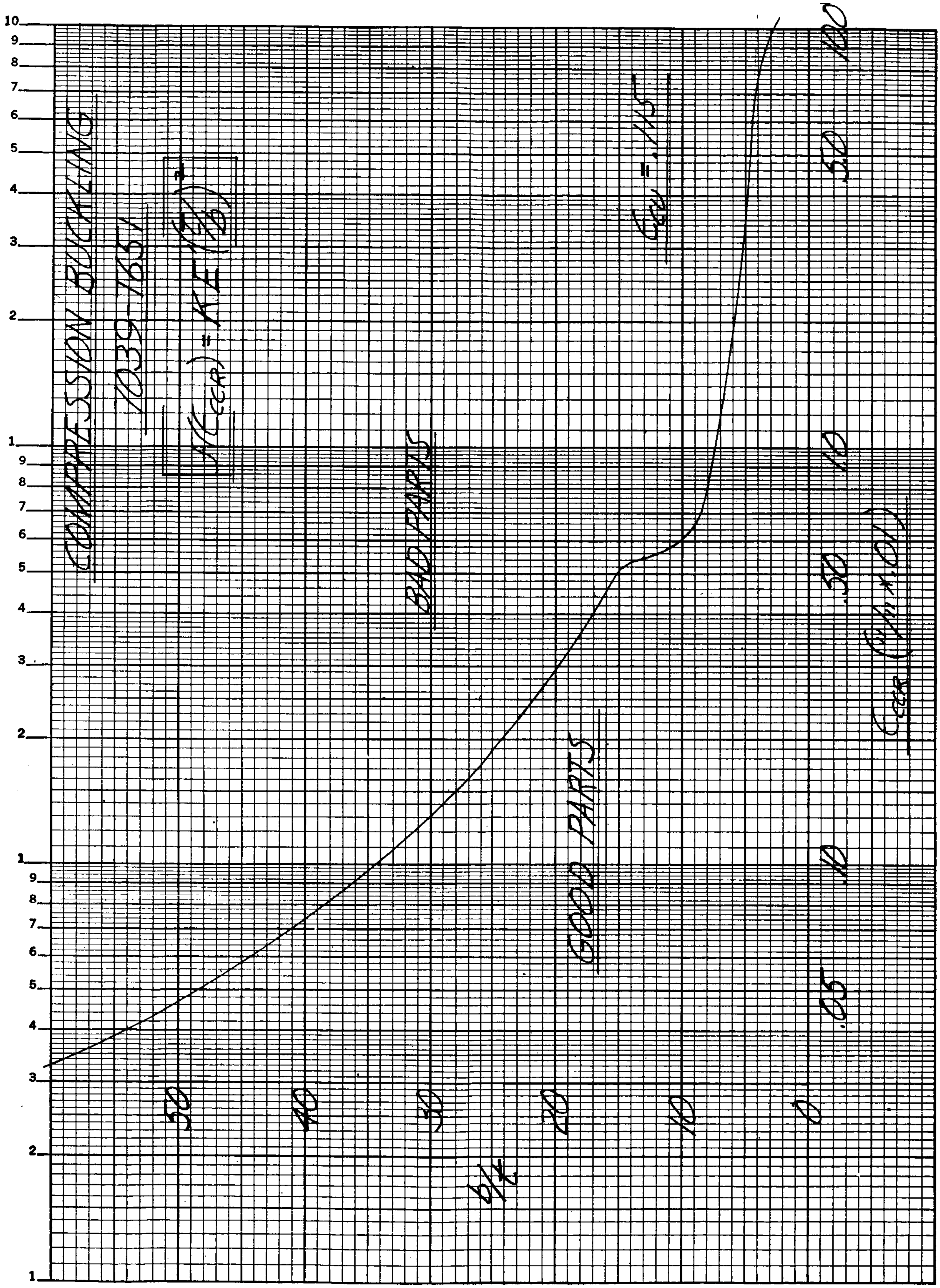
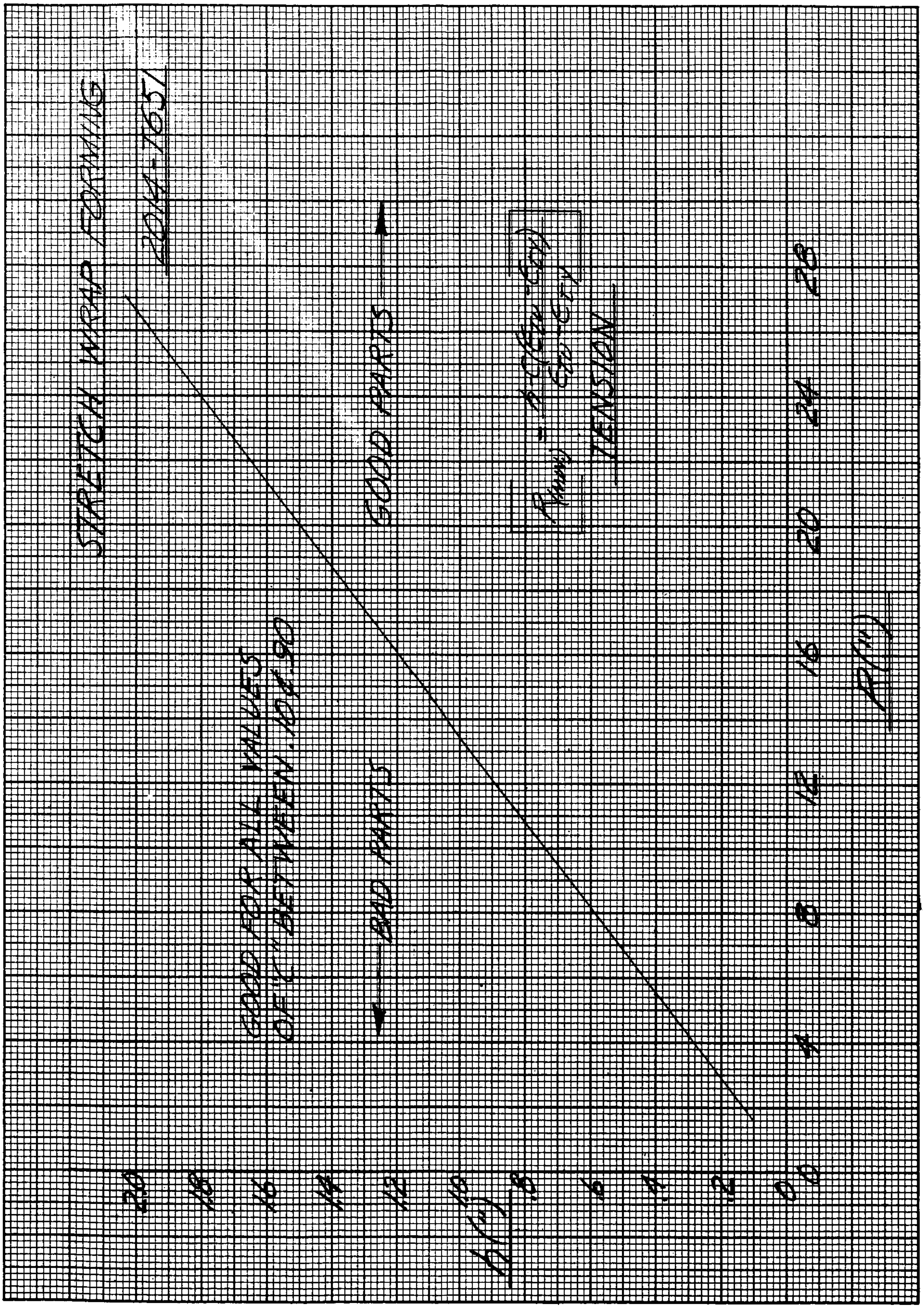
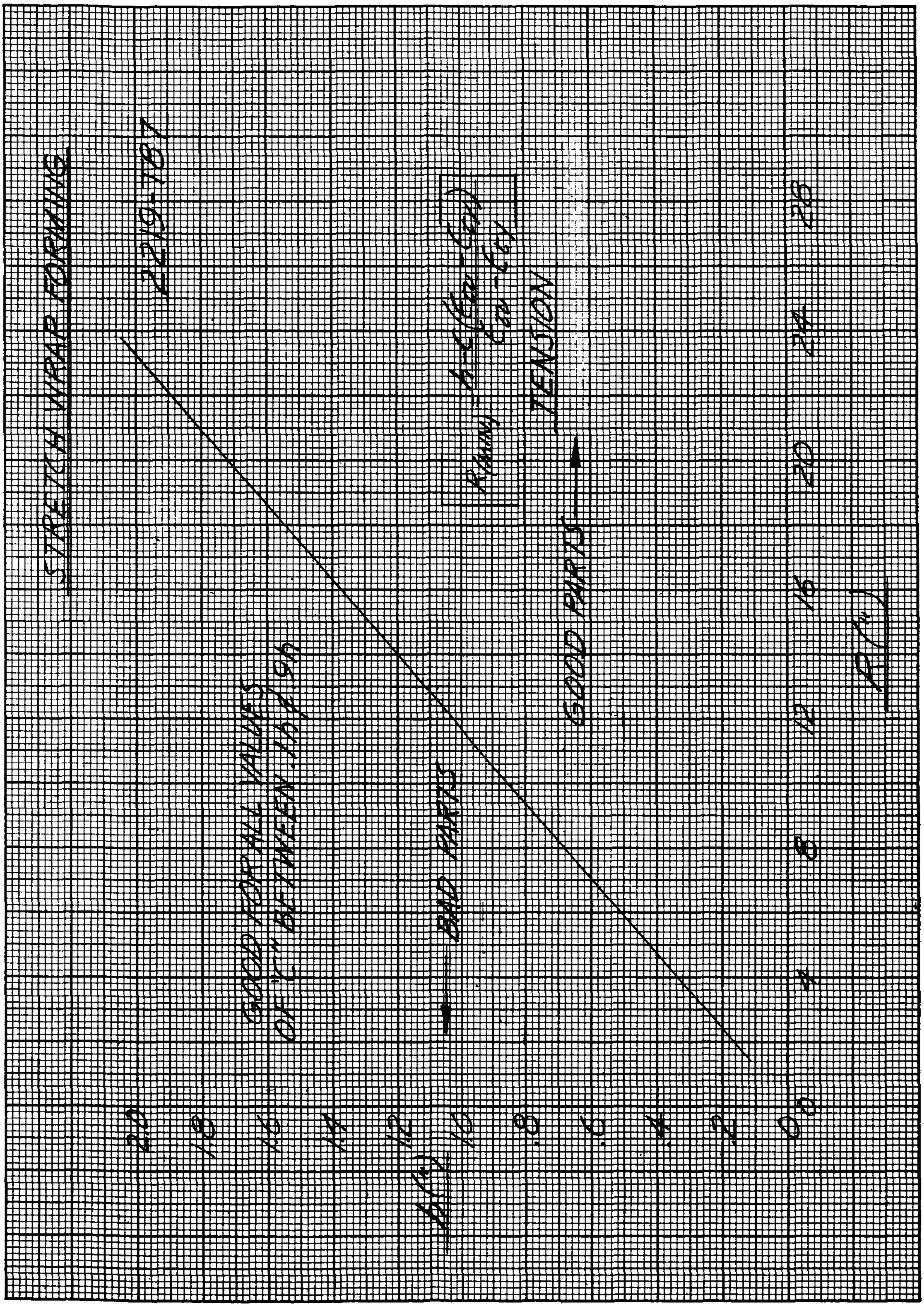

COMPRESSION BUCKLING
7D39-1651
BAD PARTS
GOOD PARTS
b/t
50
40
30
20
10
0
.05
.10
.50
1.0
5.0
10.0

FIGURE 6



STRETCH WRAP FORMING
2014-T651
GOOD FOR ALL VALUES OF "C" BETWEEN .104-.90
BAD PARTS
GOOD PARTS
TENSION
b(")
R(")
0
.2
.4
.6
.8
1.0
1.2
1.4
1.6
1.8
2.0
4
8
12
16
20
24
28

FIGURE 7



STRETCH WRAP FORMING
2219-T87
GOOD FOR ALL VALUES
OF "C" BETWEEN .15 & .94
BAD PARTS
GOOD PARTS
TENSION
2.0
1.8
1.6
1.4
1.2
1.0
.8
.6
.4
.2
0
4
8
12
16
20
24
28
h (")
R (")

FIGURE 8

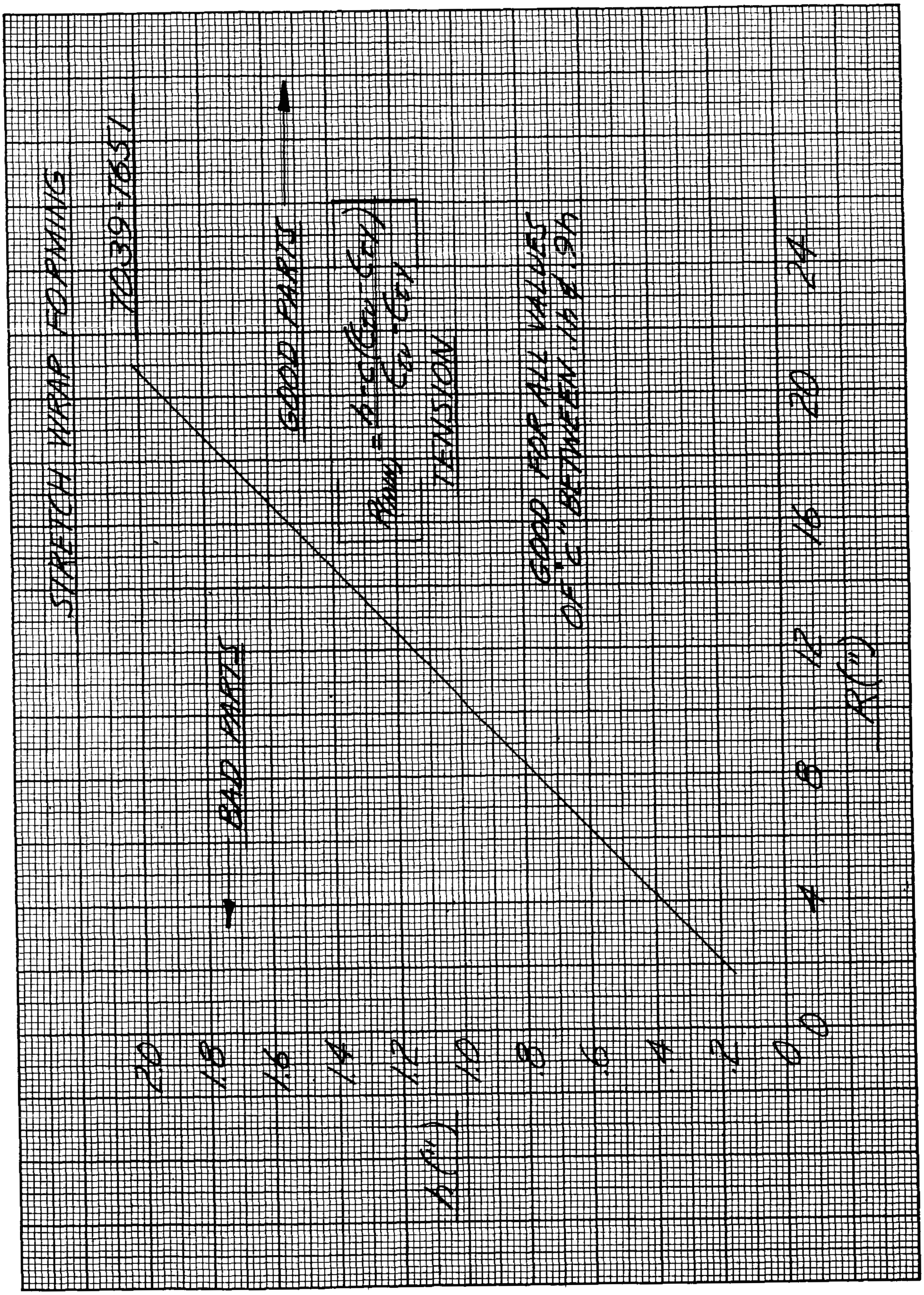

STRETCH WRAP FORMING
7039-T651
BAD PARTS
GOOD PARTS
TENSION
GOOD FOR ALL VALUES
t(")
R(")
2.0
1.8
1.6
1.4
1.2
1.0
.8
.6
.4
.2
0
4
8
12
16
20
24

FIGURE 9

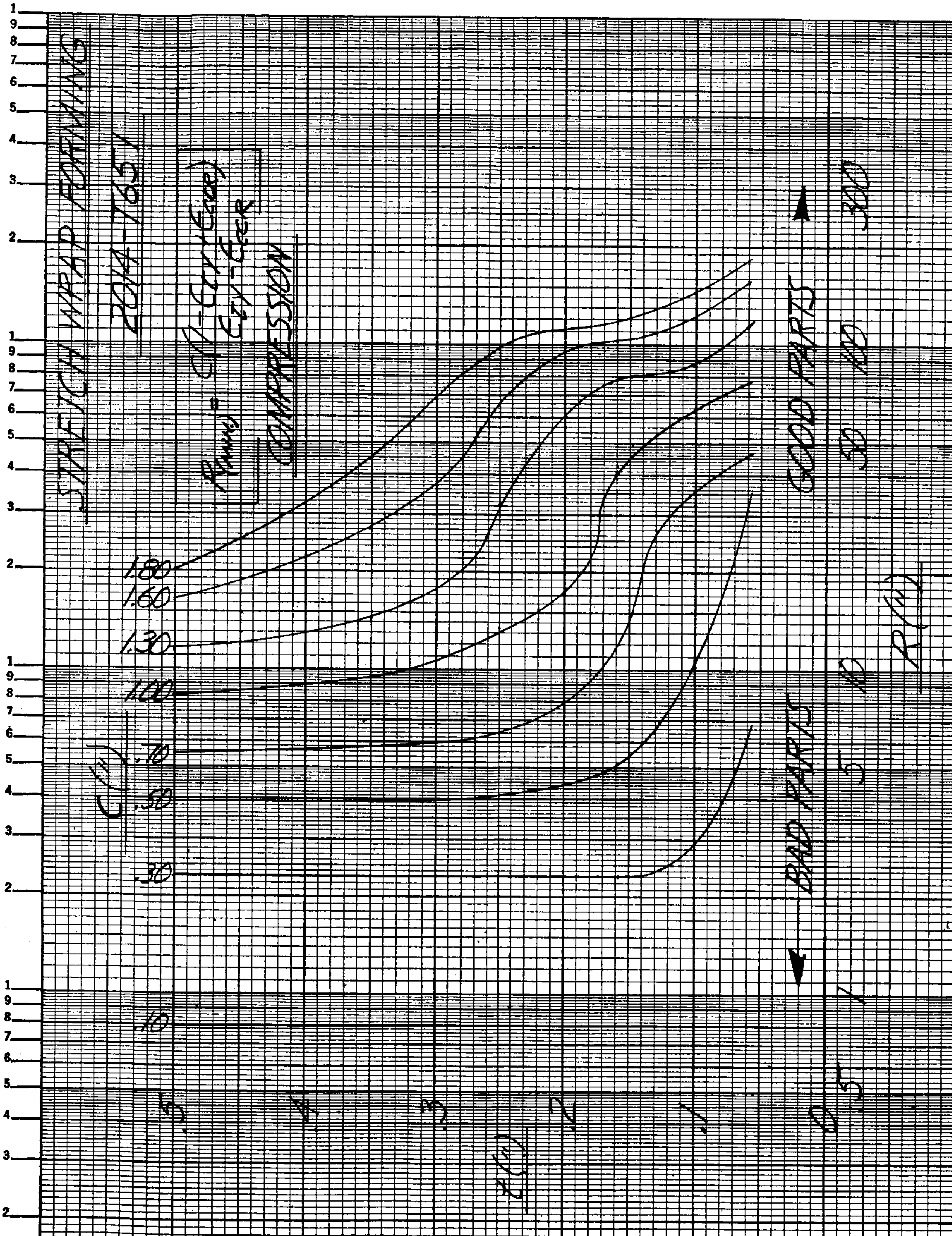

STRETCH WRAP FORMING
2014-T651
COMPRESSION
GOOD PARTS
BAD PARTS
1.80
1.60
1.30
1.00
.70
.50
.30
.10
5
4
3
2
1
0

FIGURE 10

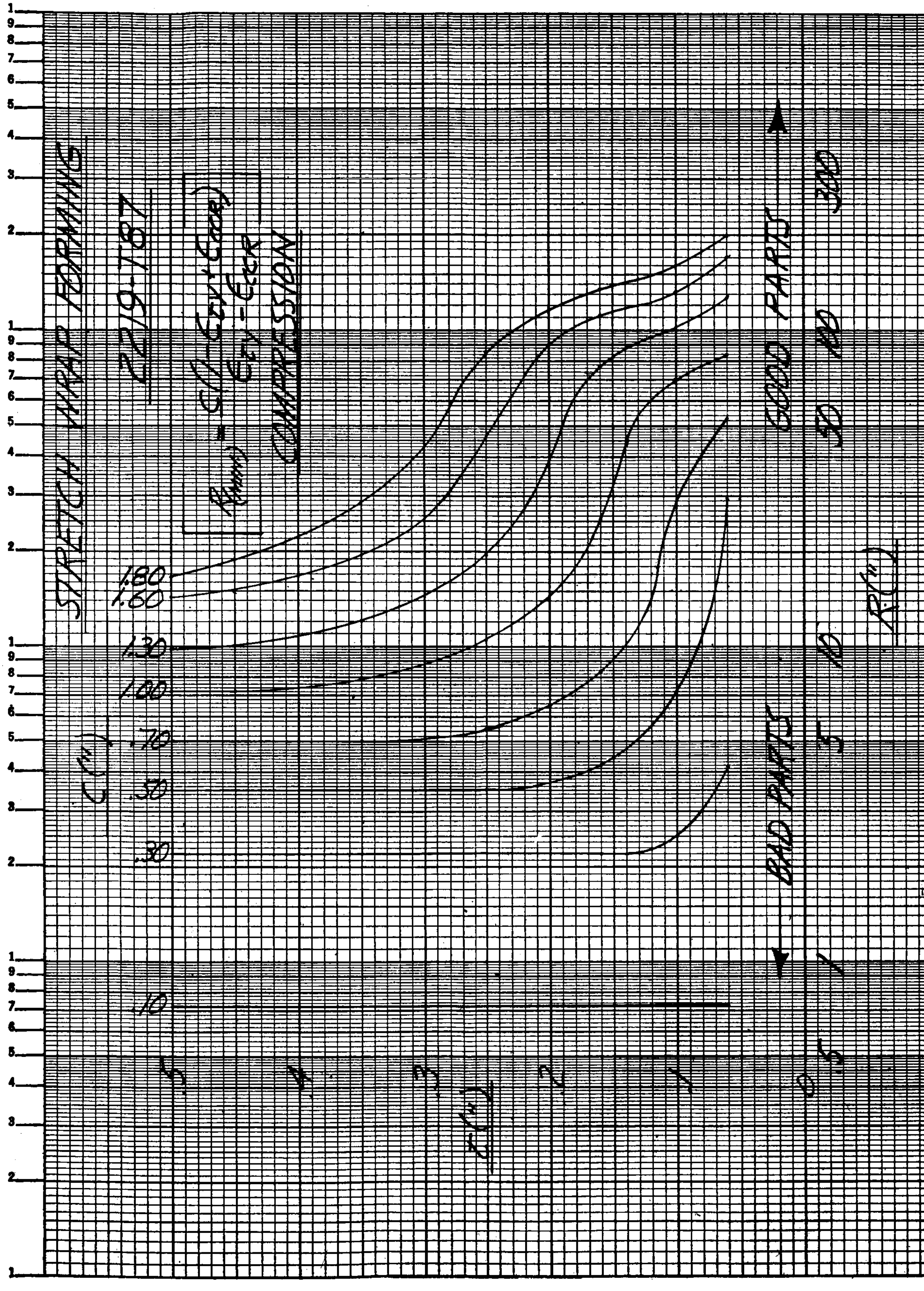

STRETCH WRAP FORMING
2219-T87
COMPRESSION
GOOD PARTS
BAD PARTS
R('')
C('')
1.80
1.60
1.30
1.00
.70
.50
.30
.10
5
4
3
2
1
0
.5
1
5
10
50
100
300

FIGURE 11

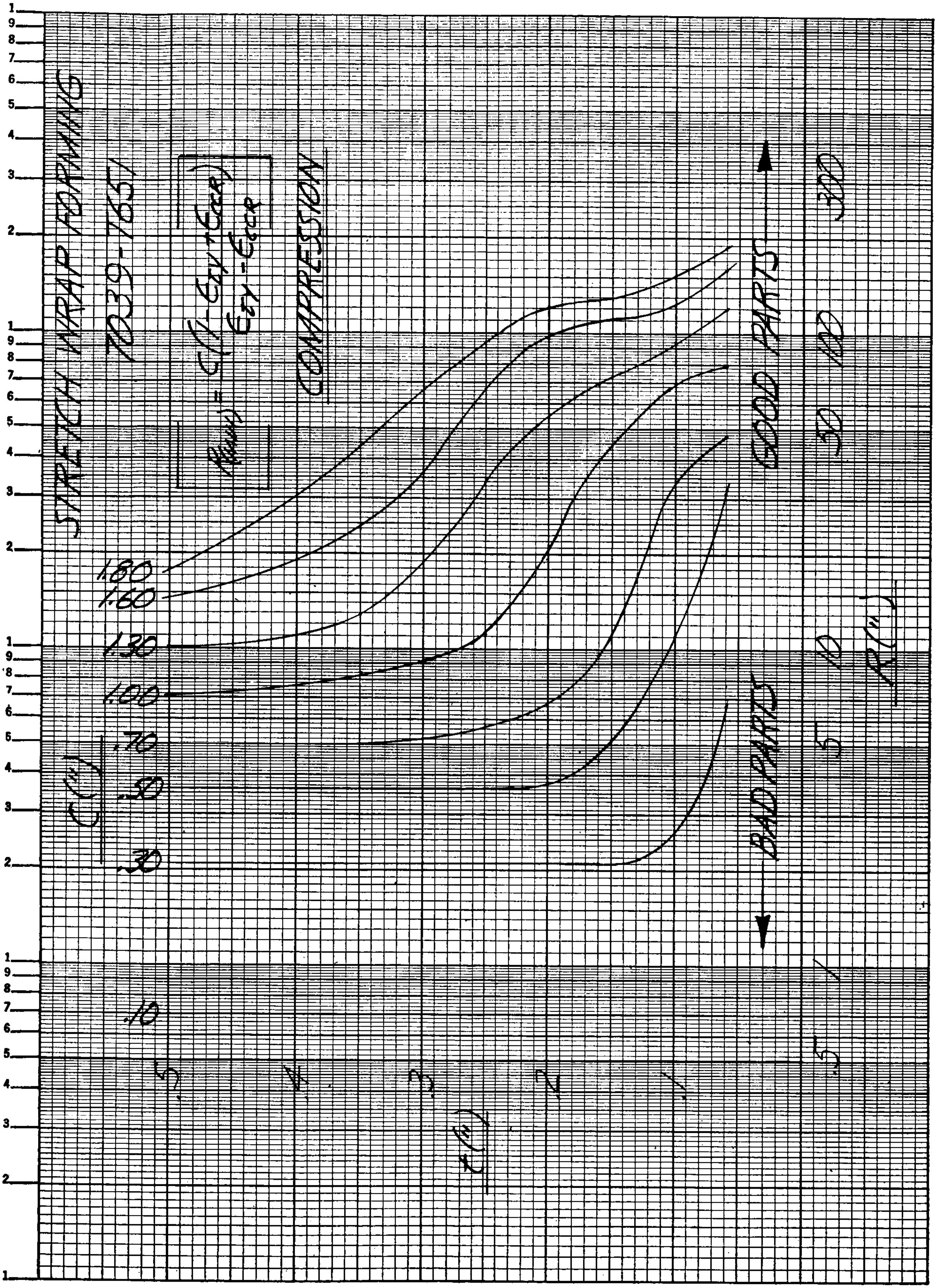

STRETCH WRAP FORMING
7039-T651
R(min) = C(1 - Ecy + Eccr) / (Ecy - Eccr)
COMPRESSION
GOOD PARTS
BAD PARTS
1.80
1.60
1.30
1.00
.70
.50
.30
.10
C(")
t(")
R(")
5
4
3
2
1
300
100
50
10
5
1
.5

FIGURE 12

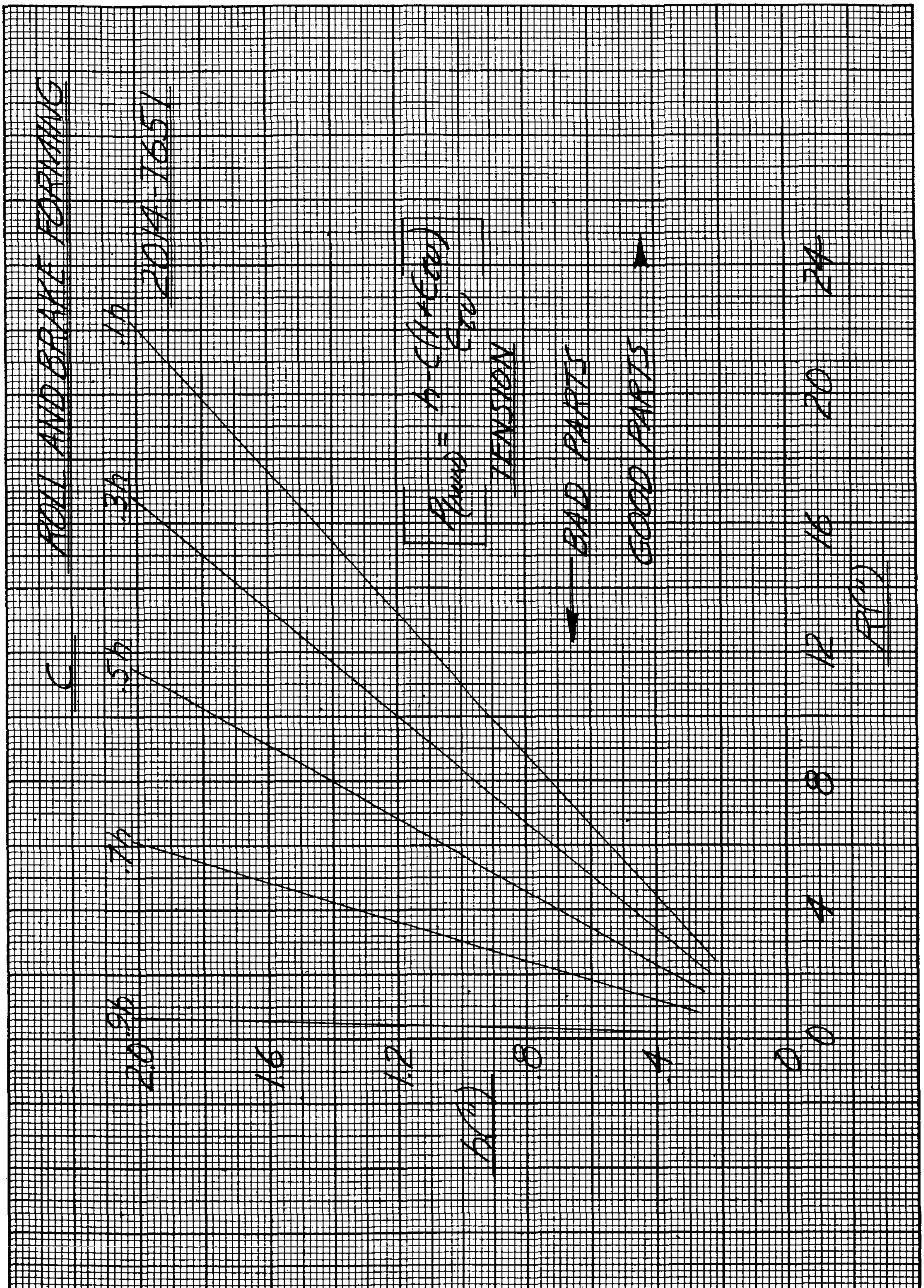

ROLL AND BRAKE FORMING
C
2014-T651
.1h
.3h
.5h
.7h
TENSION
BAD PARTS
GOOD PARTS
2.0
1.6
1.2
.8
.4
0
4
8
12
16
20
24

FIGURE 13

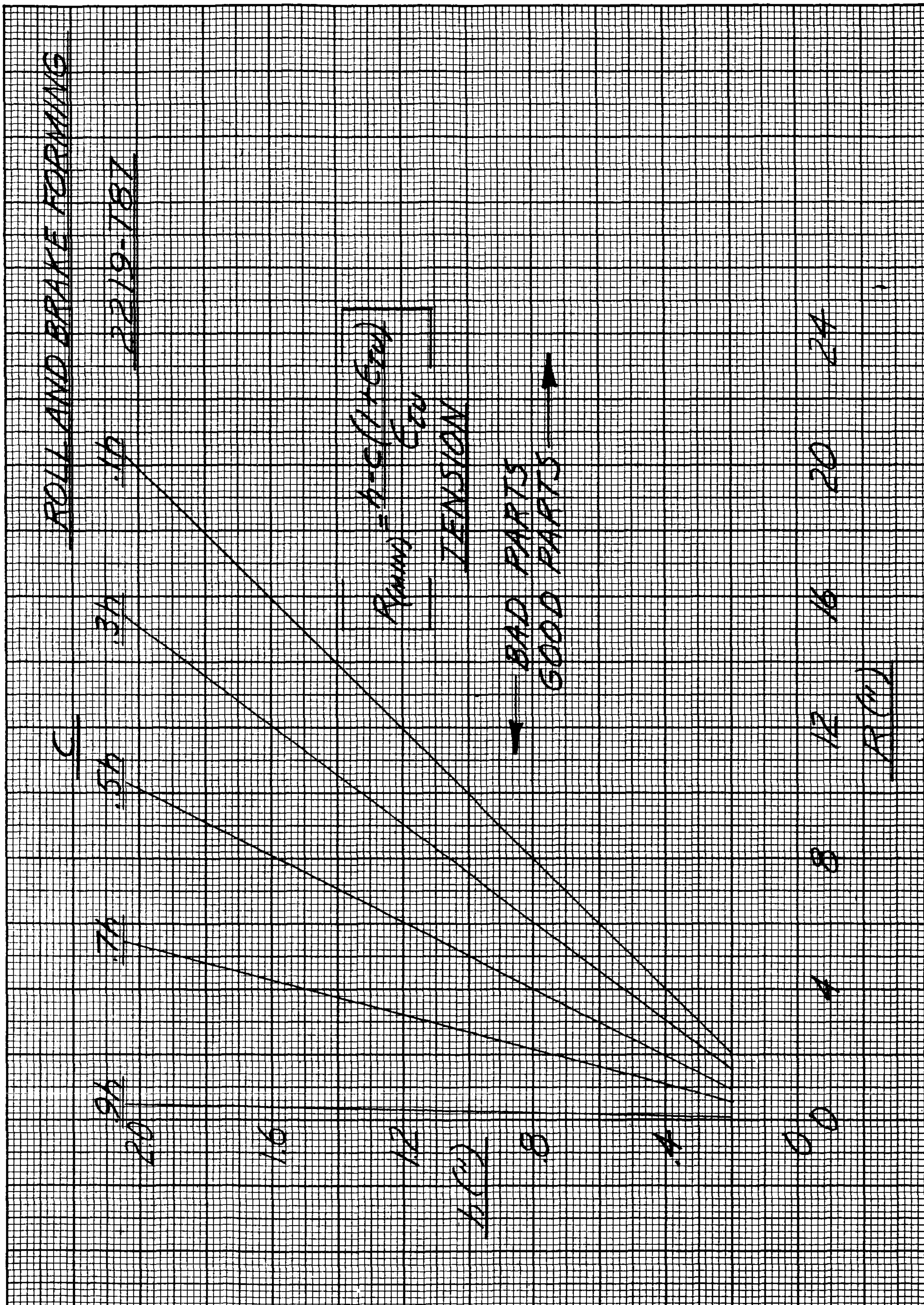

ROLL AND BRAKE FORMING
2219-T87
C
.1h
.3h
.5h
.7h
.9h
$R_{min} = \frac{h - C(1 + e_{tu})}{e_{tu}}$
TENSION
← BAD PARTS
GOOD PARTS →
h(")
0
.4
.8
1.2
1.6
2.0
R(")
0
4
8
12
16
20
24

FIGURE 14

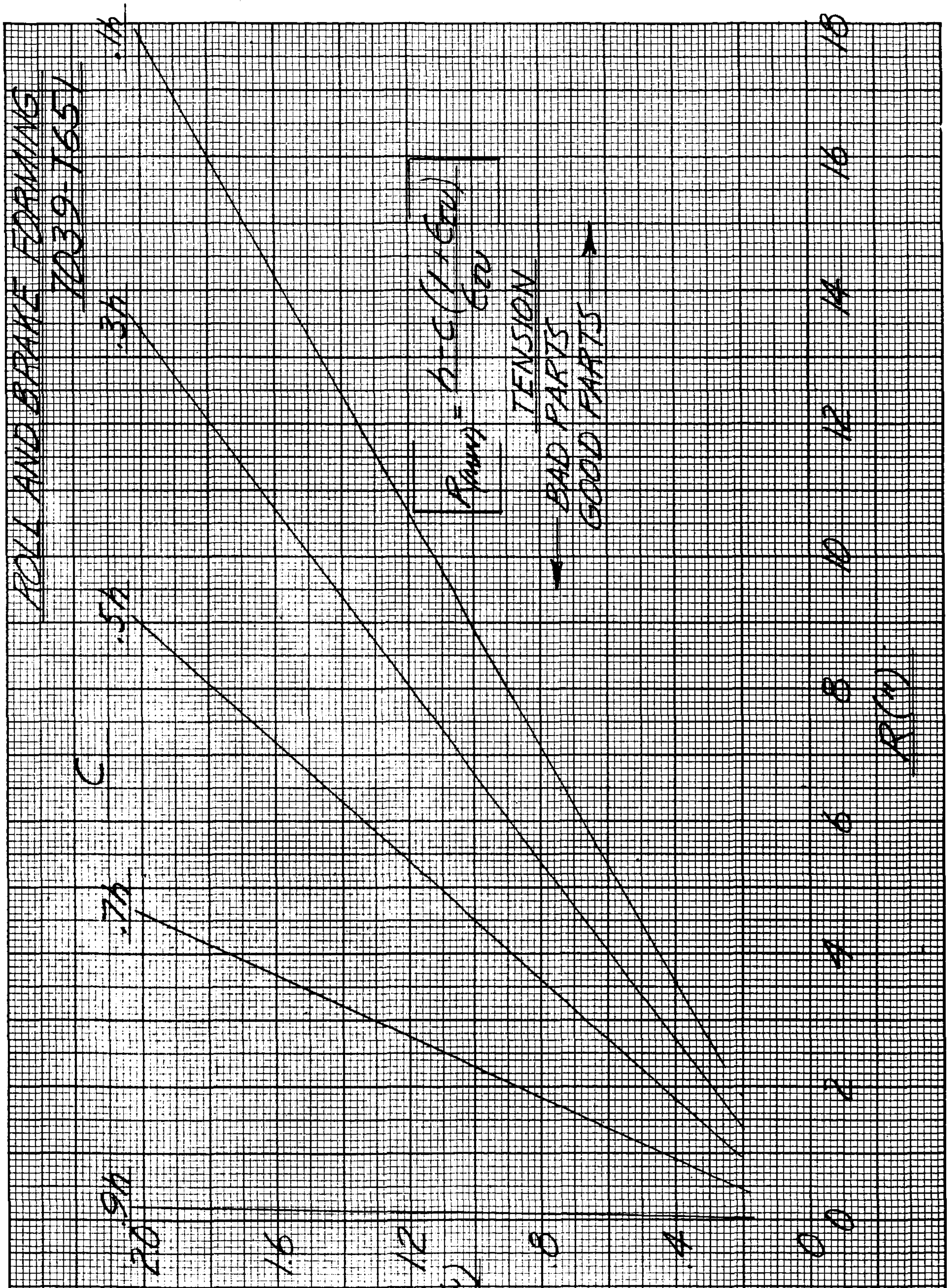

ROLL AND BRAKE FORMING
7039-T65)
$R_{(min)} = \frac{h - C(1+e_{TU})}{e_{TU}}$
TENSION
BAD PARTS
GOOD PARTS
C
.1h
.3h
.5h
.7h
.9h
R('')
h('')
2.0
1.6
1.2
.8
.4
0
0
2
4
6
8
10
12
14
16
18

FIGURE 15

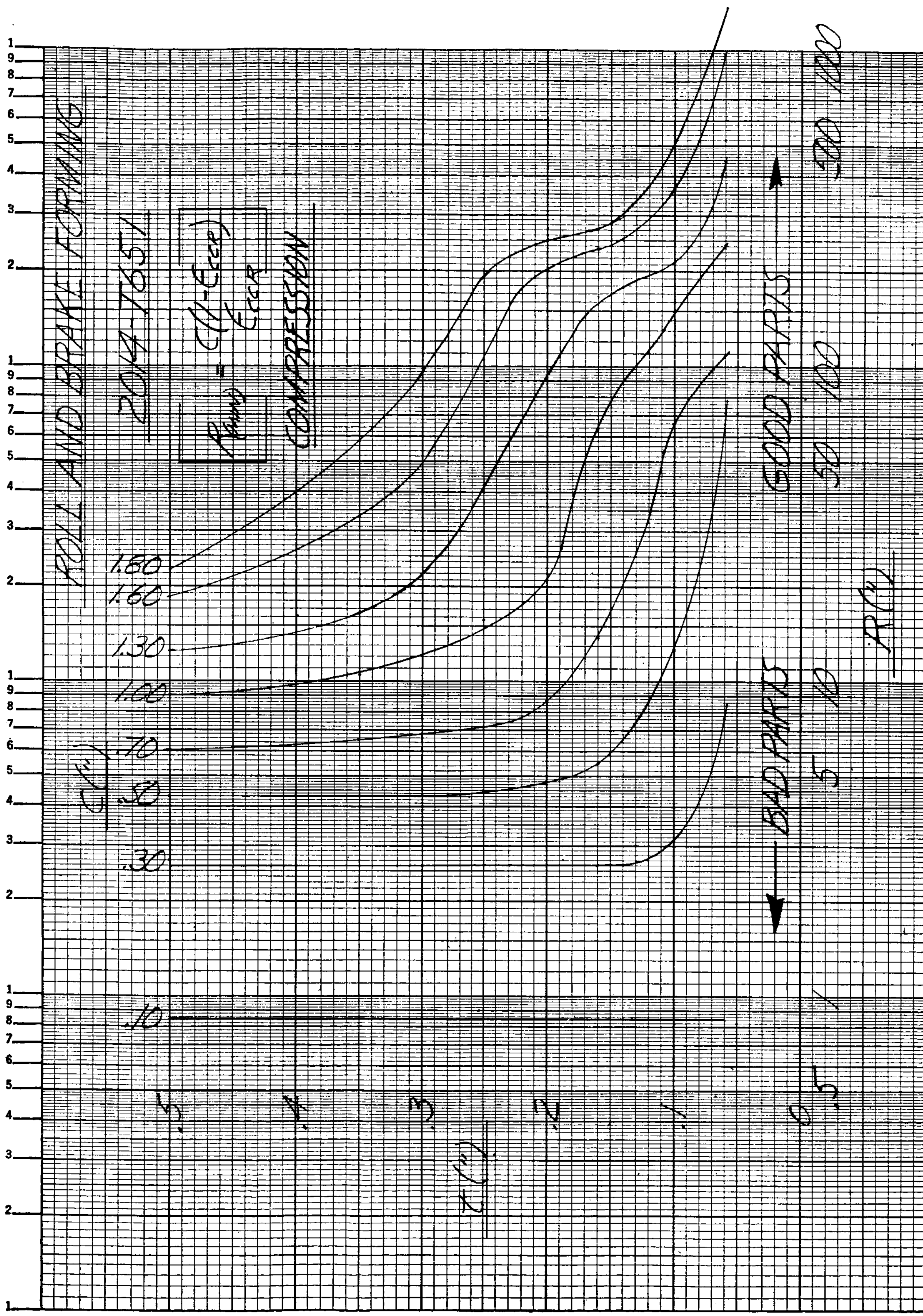

ROLL AND BRAKE FORMING
2014-T651
COMPRESSION
GOOD PARTS
BAD PARTS
R(")
C(")
t(")
1.80
1.60
1.30
1.00
.70
.50
.30
.10
5
10
50
100
500
1000
.5
.4
.3
.2
.1
0

FIGURE 16

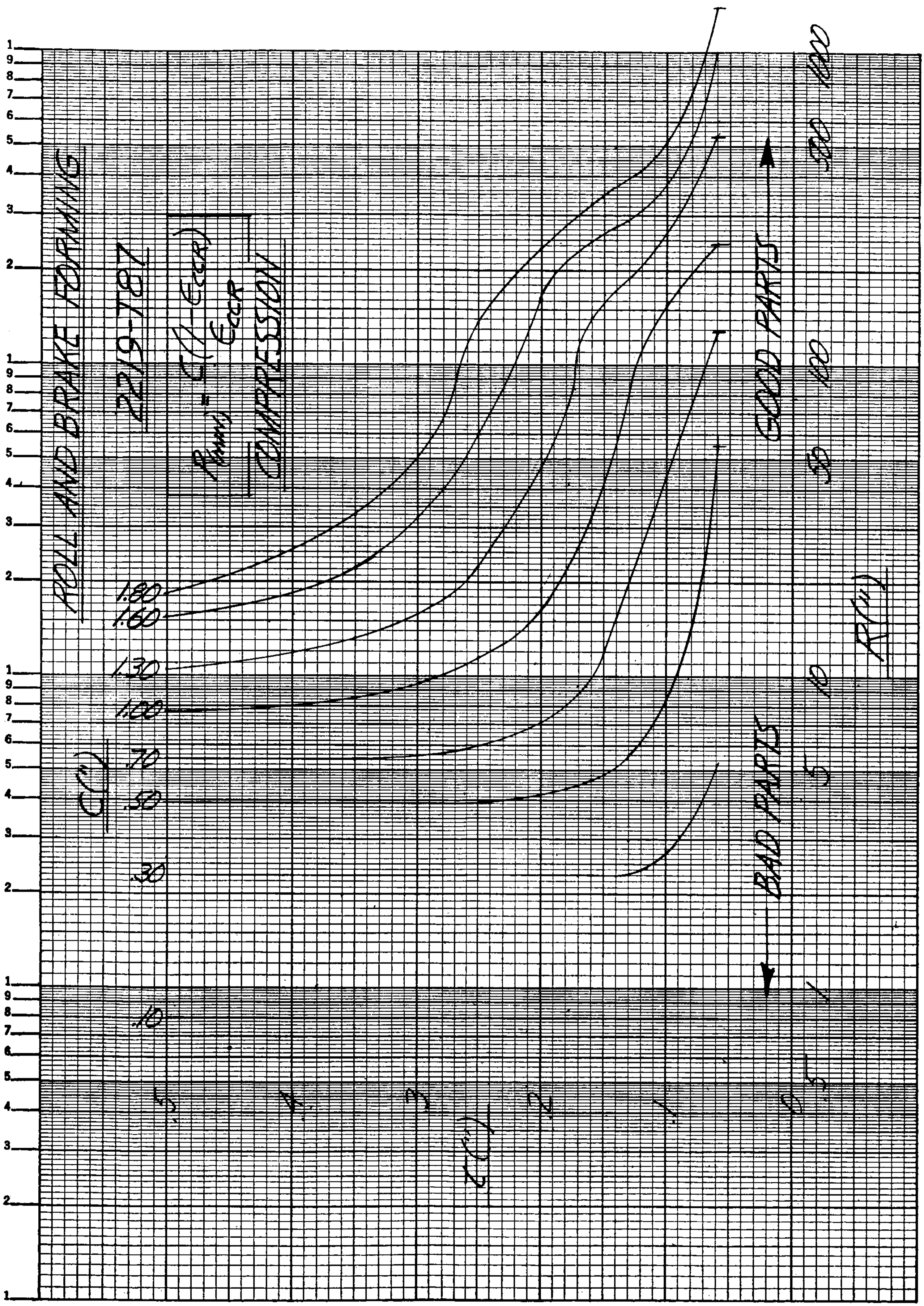

ROLL AND BRAKE FORMING
2219-T87
$R_{(min)} = C\left(\frac{1-E_{CCR}}{E_{CCR}}\right)$
COMPRESSION
GOOD PARTS
BAD PARTS
R(")
C(")
1.80
1.60
1.30
1.00
.70
.50
.30
.10
1000
500
100
50
10
5
1
.5
5
4
3
2
1
.5

FIGURE 17

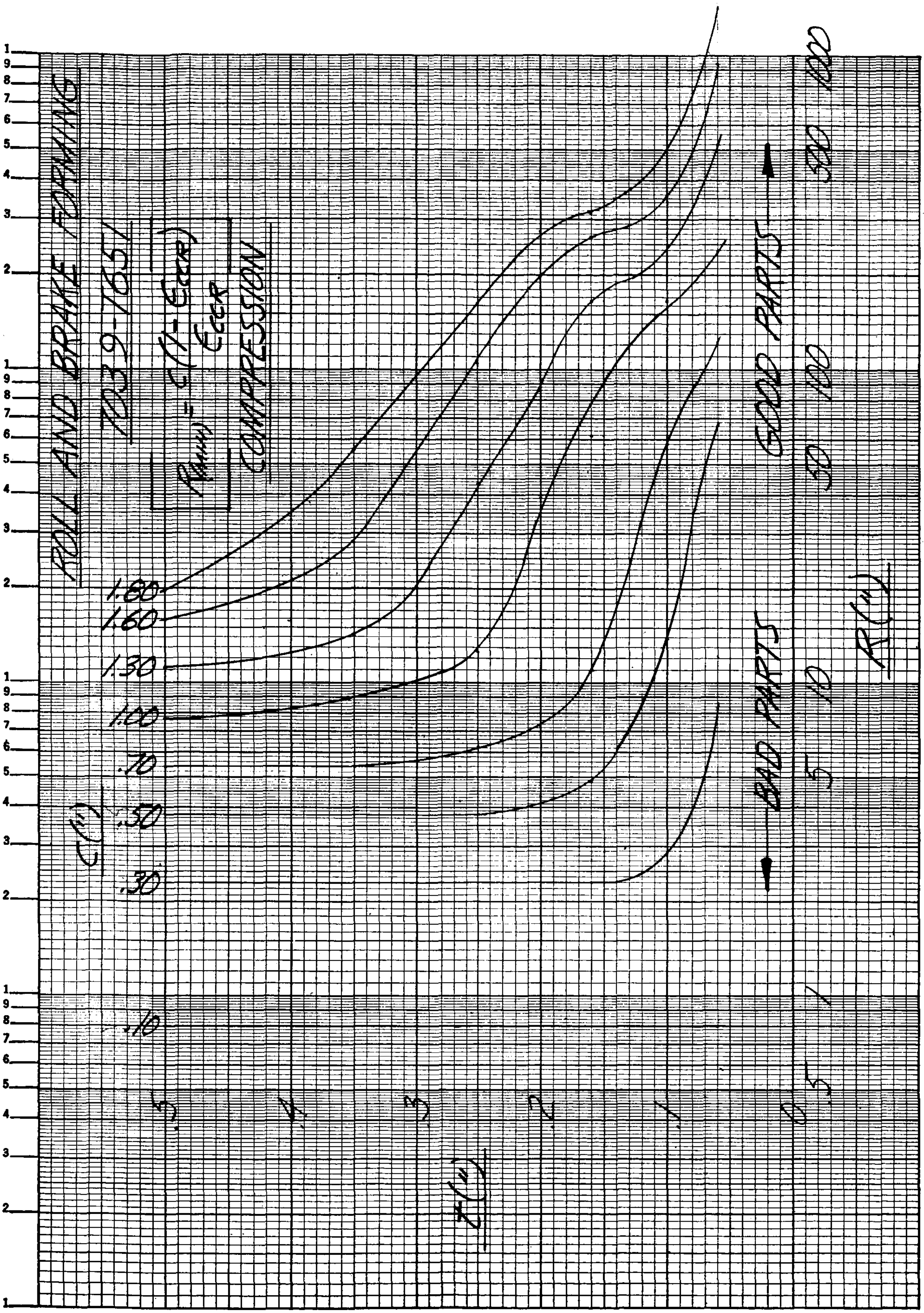

ROLL AND BRAKE FORMING
7039-T651
$R_{(min)} = \frac{C(1-\epsilon_{CCR})}{\epsilon_{CCR}}$
COMPRESSION
GOOD PARTS
BAD PARTS
R(")
C(")
T(")
1.80
1.60
1.30
1.00
.70
.50
.30
.10

FIGURE 18

4/ TEST DATA

4.1 ROLL FORM TEST PANELS

Test panels were machined from 7039-T651 aluminum plate material to the representative configurations as shown in Sketches A and B. A thermosetting casting epoxy system with flexicizer added to produce a hardness reading of 45 on a Type D durometer was used as the filler material. The filler height extended 0.10-inch above all rib edges.

The prepared sections were formed on pyramid-type rolling equipment which utilized two 3-inch diameter bottom rolls set at a 4.7-inch span and a 2.75-inch diameter upper bending roll. Steel plate 0.190-inch thick, prerolled to the test radius of 24 inches, was used as a starter plate and .010-inch thick steel sheet was used as a call sheet. The 90-degree rib panel was contoured to a 24-inch radius cylindrical segment in 10 passes. The forming of the 45-degree rib panel was discontinued when rib buckling became evident.

After removal of the filler, the panels were inspected with the results tabulated below:

90-Degree Rib Pattern

Calculated minimum radius		36.0"
Deviation from 24-inch radius	±	.012"
Lateral Bow	±	.015"
Change in thickness of parallel ribs	+	.015"
Change in thickness of parallel weld flange	+	.020"
Measured strain of outer fibers	+	.0058"/in.
Measured strain of inner fibers	-	.0393"/in.
Calculated strain of outer fibers	+	.0082"/in.
Calculated strain of inner fibers	-	.0321"/in.
Fractures	None	

45-Degree Rib Pattern

Calculated minimum radius		12.0"
Deviation from 26-inch radius	±	.020"
Lateral Bow	±	.013"
Change in thickness of ribs	+	.006"
Change in thickness of parallel weld flange	+	.006"
Measured strain of outer fibers	+	.0044"/in.
Measured strain of inner fibers	-	.0354"/in.
Calculated strain of outer fibers	+	.0092"/in.
Calculated strain of inner fibers	-	.0281"/in.
Fractures	Yes (see Sketch B, sheet 1)	

Yielding of the free edge of the ribs was evident on both configurations. This was caused by the high bearing load developed because of the short span of the bottom rolls.

Photographs showing each configuration before and after forming are presented on pages 4-11, 4-12, 4-13, and 4-14.

4.1.1 MINIMUM RADIUS CALCULATIONS

<u>90-Degree Rib Pattern</u> (reference page 4-7, Sketch A)

Moment of inertia	=	$.192''^4$
h	=	1.015" (actual)
c	=	.796"
t	=	.140" (actual)

Tension criteria limit:

R = 1.75" (reference Figure 15, page 3-17)

Compression criteria limit:

R = 36.0" (reference Figure 18, page 3-20)

This is the minimum radius

<u>45-Degree Rib Pattern</u> (reference page 4-9, Sketch B)

Moment of inertia	=	$.231''^4$
h	=	1.015" (actual)
c	=	.754"
t	=	.127/.707 = .179 (actual)

Tension criteria limit:

R = 2.0" (reference Figure 15, page 3-17)

Compression criteria limit:

R = 12.0" (reference Figure 18, page 3-20)

This is the minimum radius.

4.1.2 STRAIN CALCULATIONS

<u>90-Degree Rib Pattern</u> (reference page 4-7, Sketch A)

Moment of inertia	=	.192"^{4}
h	=	1.015"
c	=	.796"

Tension fibers: (reference equation 16, page 2-10)

$$\frac{h - c}{R + c} = \epsilon_t$$

$$\frac{1.015 - .796}{24.0 + .796} = \epsilon_t$$

$$\epsilon_t = .00883''/\text{in.}$$

Compression fibers: (reference equation 17, page 2-10)

$$\frac{c}{R + c} = \epsilon_c$$

$$\frac{.796}{24.0 + .796} = \epsilon_c$$

$$\epsilon_c = .0321''/\text{in.}$$

4.1.2 STRAIN CALCULATIONS (continued)

45-Degree Rib Pattern (reference page 4-9, Sketch B)

Moment of inertia	=	$.231''^4$
h	=	1.015"
c	=	.754"

Tension fibers: (reference equation 16, page 2-10)

$$\frac{h - c}{R + c} = \epsilon_t$$

$$\frac{1.015 - .754}{26.0 + .754} = \epsilon_t$$

$$\epsilon_t = .00975''/\text{in.}$$

Compression fibers: (reference equation 17, page 2-10)

$$\frac{c}{R + c} = \epsilon_c$$

$$\frac{.754}{26.0 + .754} = \epsilon_c$$

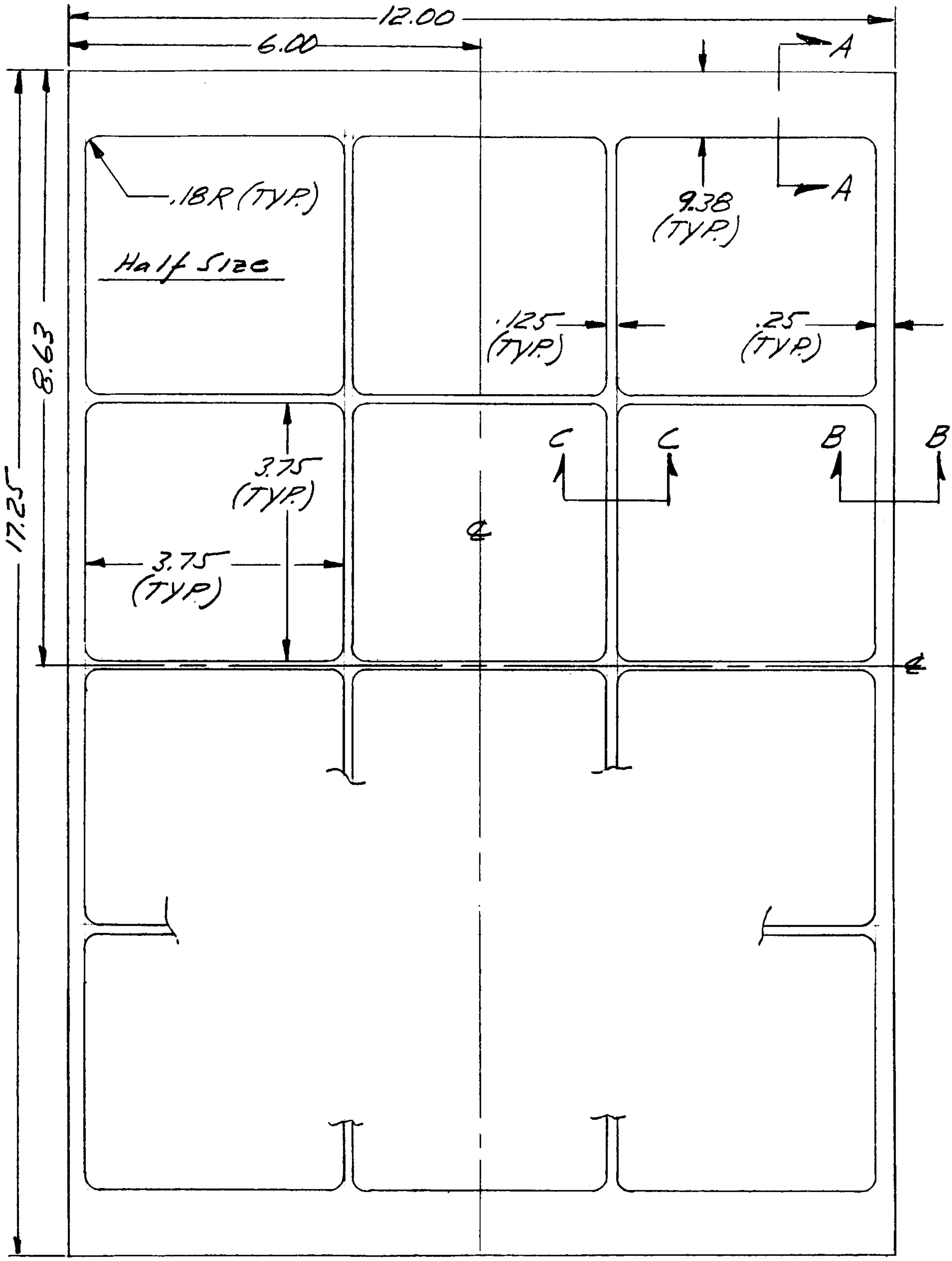
$$\epsilon_c = .0282''/\text{in.}$$

4.1.3 CONCLUSIONS, FORMING OF 90-DEGREE RIB PATTERN

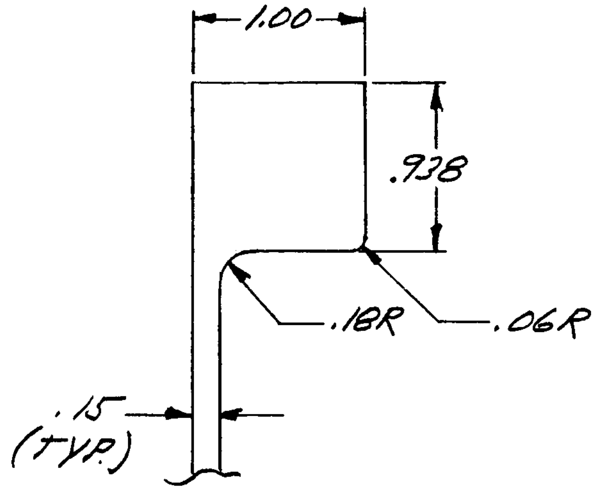
The results of forming the 90-degree rib pattern agreed reasonably well with the derived theory. The excessive roll pressure, due to the too short span between lower rolls, caused bearing deformation along the rib edges. Additionally, this high load creates an axial compression load which could well have the effect of significantly raising the neutral axis toward the outer fiber. This is substantiated by the relation of the actual strains to the theoretical strains. Theory is somewhat conservative due to the very effective rib support provided by the epoxy fillers allowing a higher compressive stress then the buckling theory indicates.

4.1.4 CONCLUSIONS, FORMING OF 45-DEGREE RIB PATTERN

The results of forming the 45-degree rib pattern did not agree reasonably well with theory. The primary reason being that theory is predicated on axial forces only and does not account for component forces and bending moments induced in the upstanding ribs due to their orientation from the direction of roll. The fairly consistent bowing of the ribs indicates a considerable bending moment. Failure could be assumed to be similar to that of a beam column. All the effects noted in the 90-degree rib pattern specimen are also evident in the 45-degree rib pattern further substantiating the conclusions which were reached.

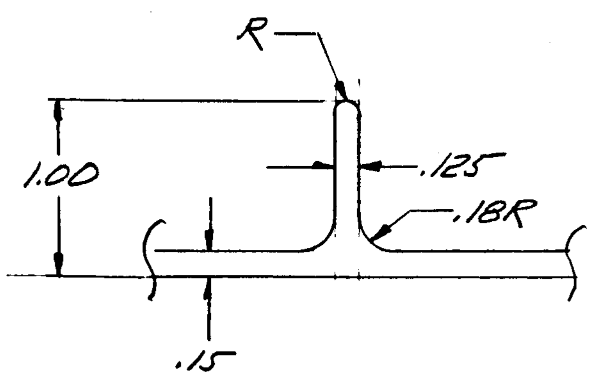


90° RIB, SKETCH A — SHEET 1 OF 2

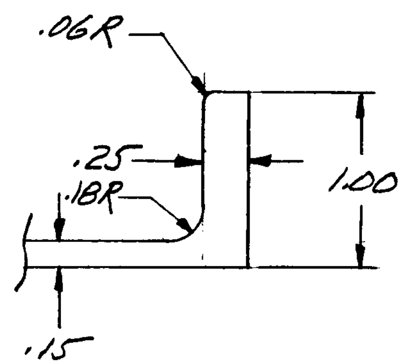


A-A

Full Size

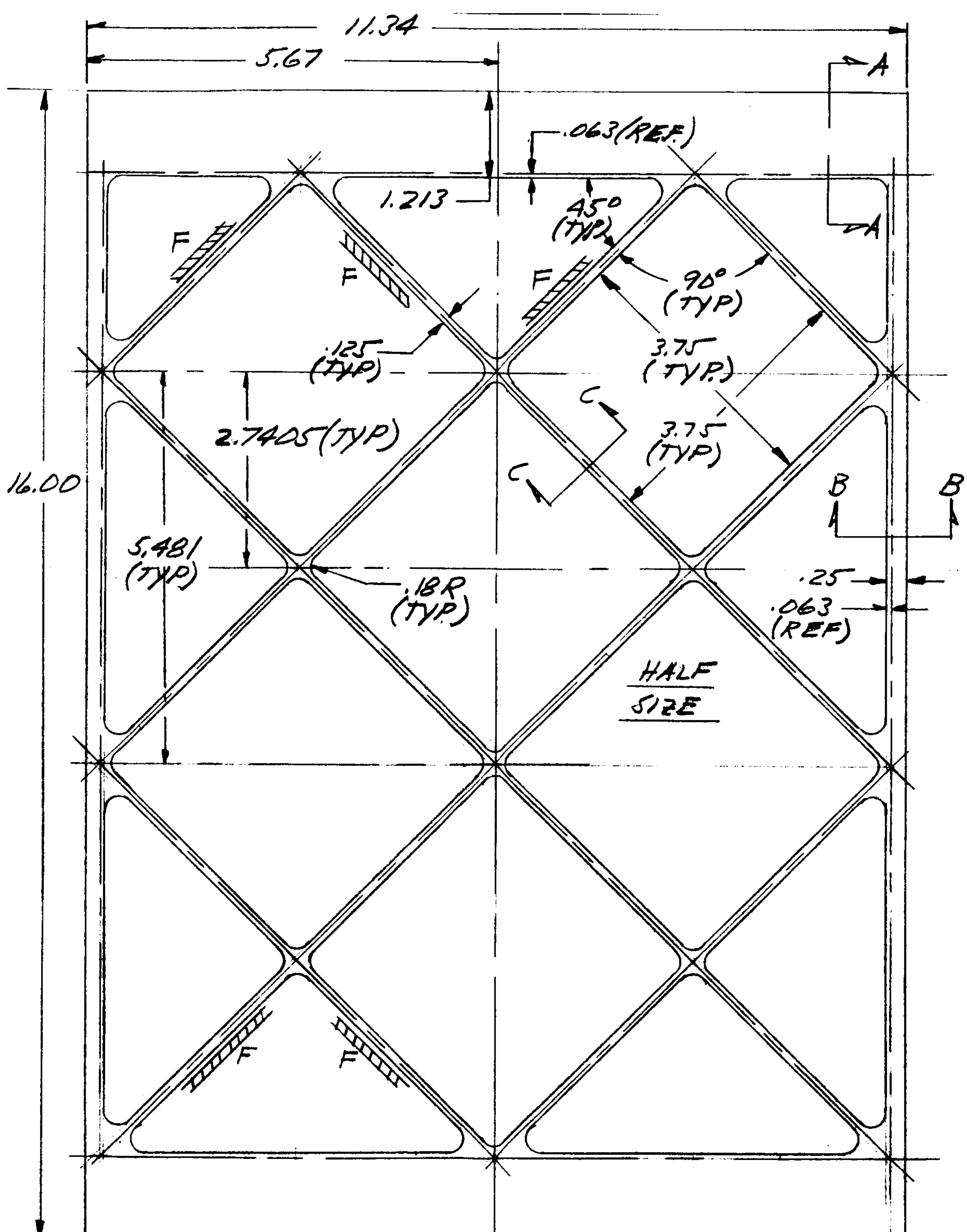


C-C



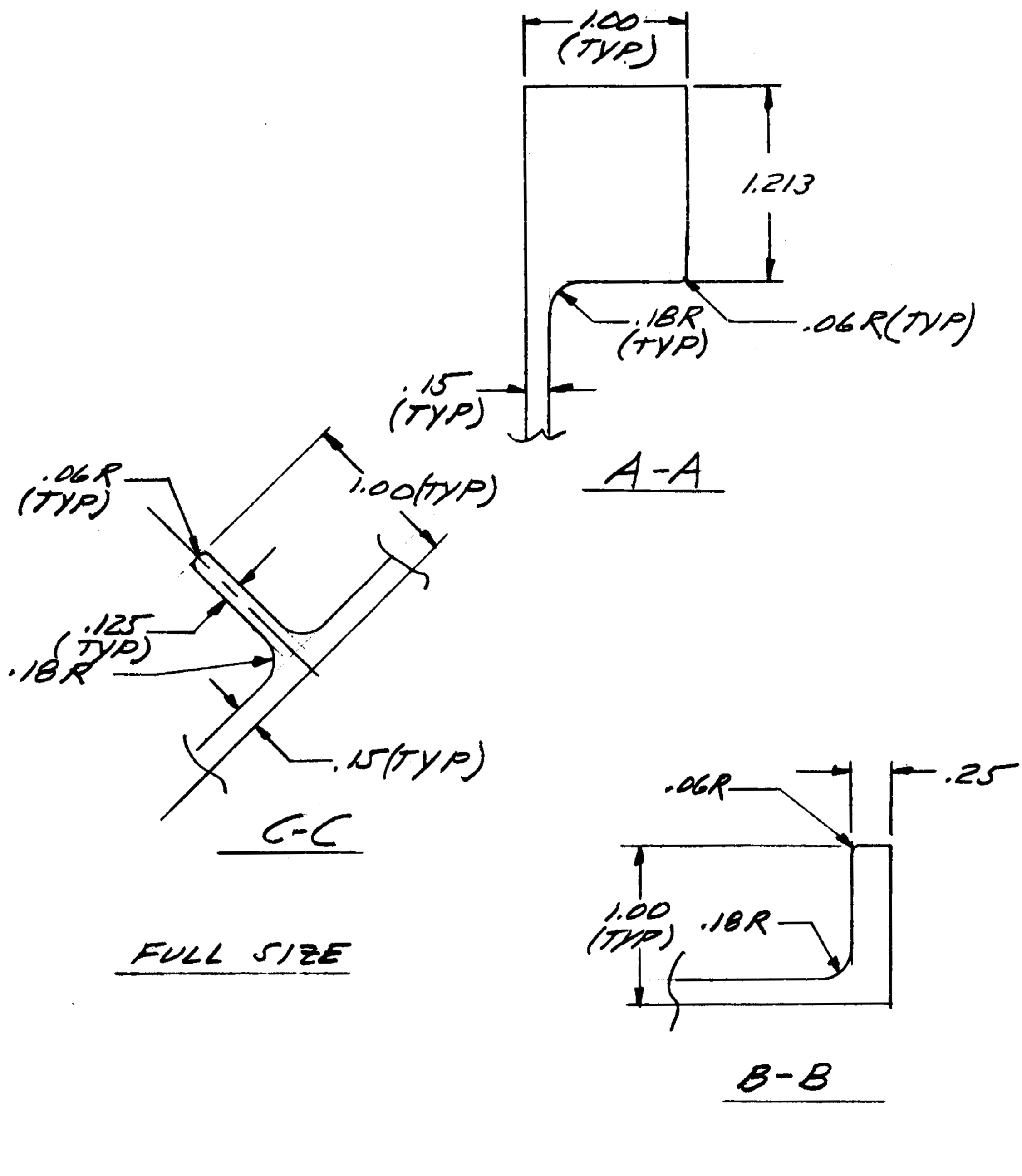
B-B

90° RIB, SKETCH A — SHEET 2 OF 2



F — Denotes fracture of rib along tangency point of inside radius.

45° RIB, SKETCH B — SHEET 1 OF 2



45° RIB, SKETCH B — SHEET 2 OF 2

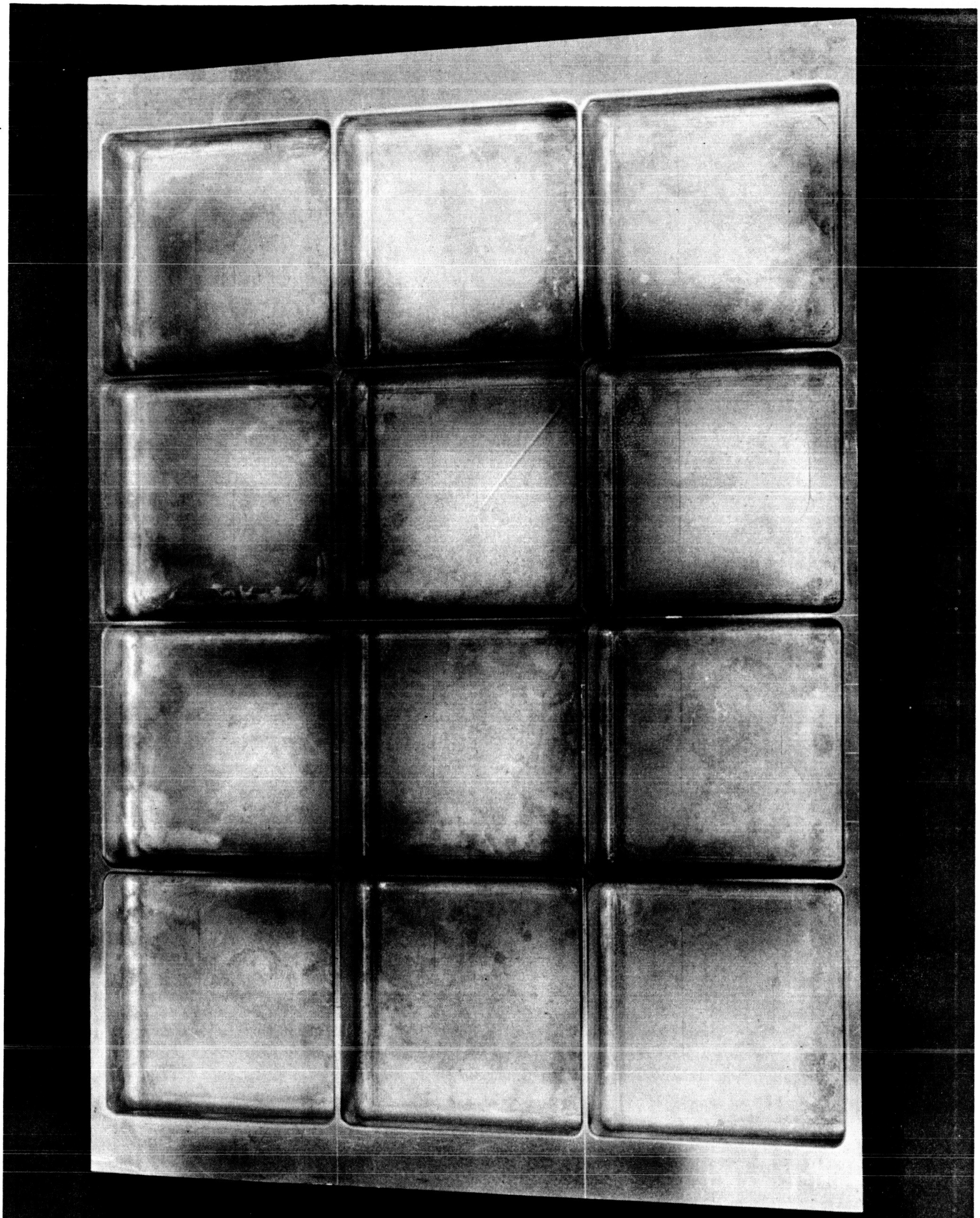


Photo 1. 90-degree Rib Pattern before forming.

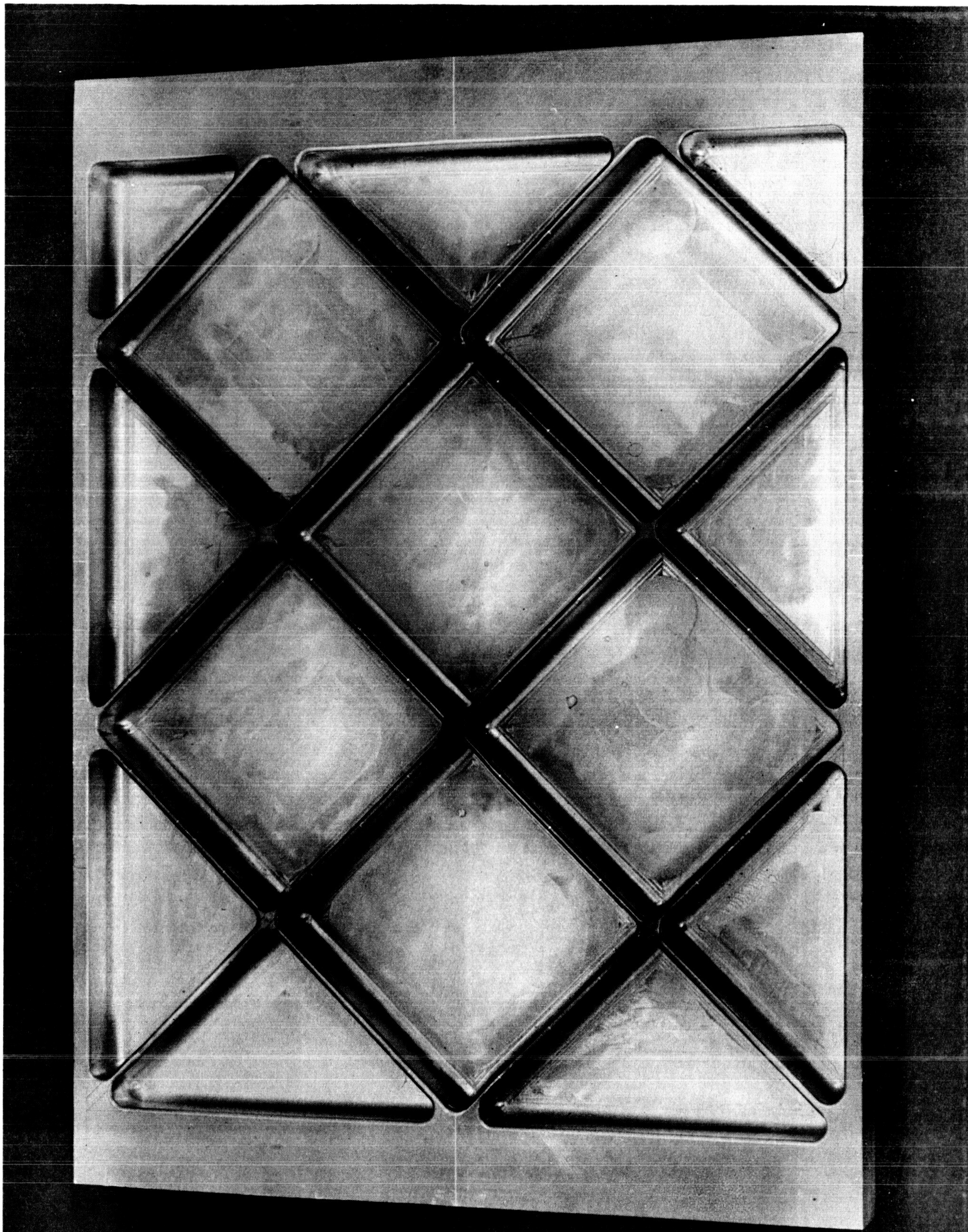


Photo 2. 45-degree Rib Pattern before forming.

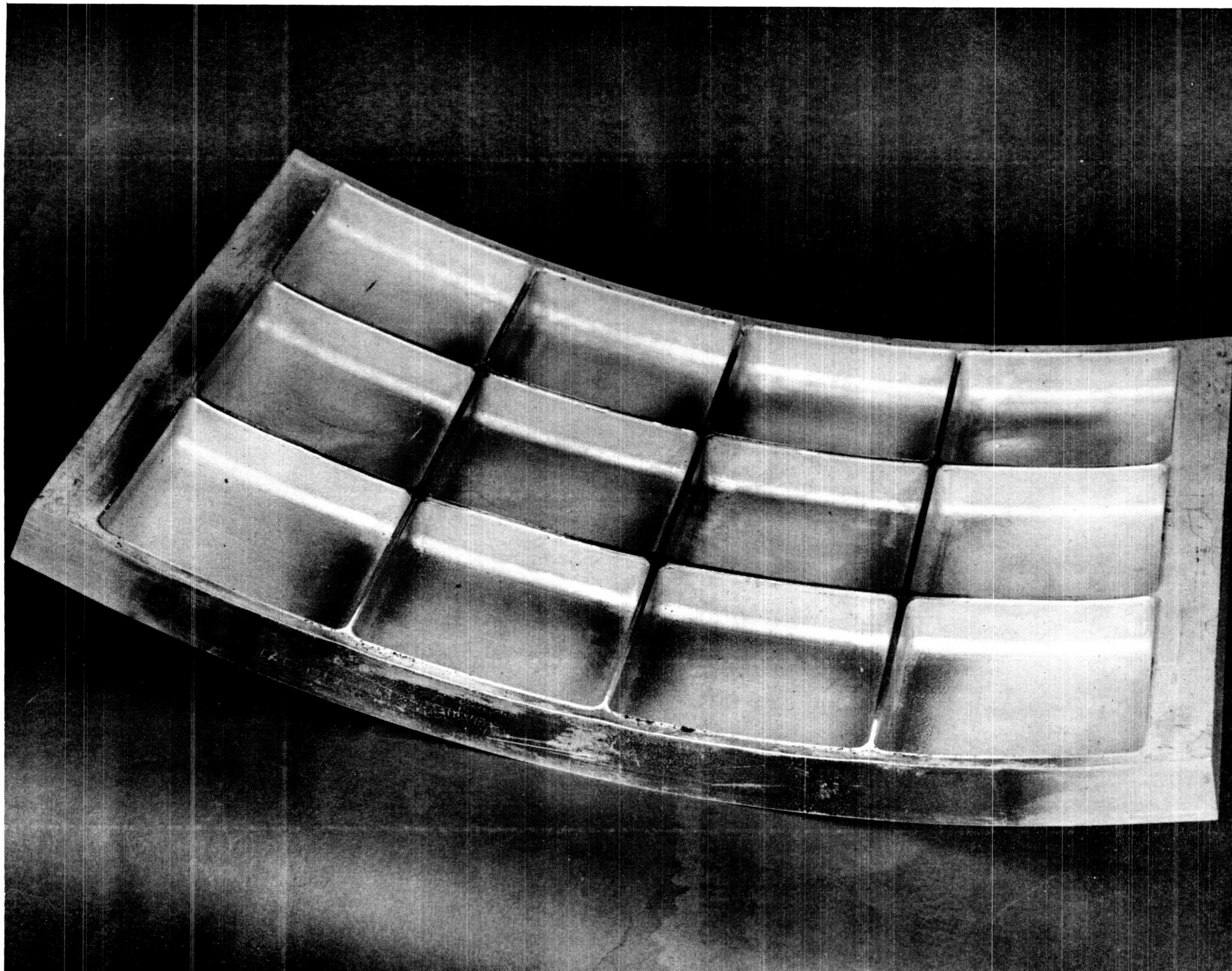


Photo 3. 90-degree Rib Pattern after forming.

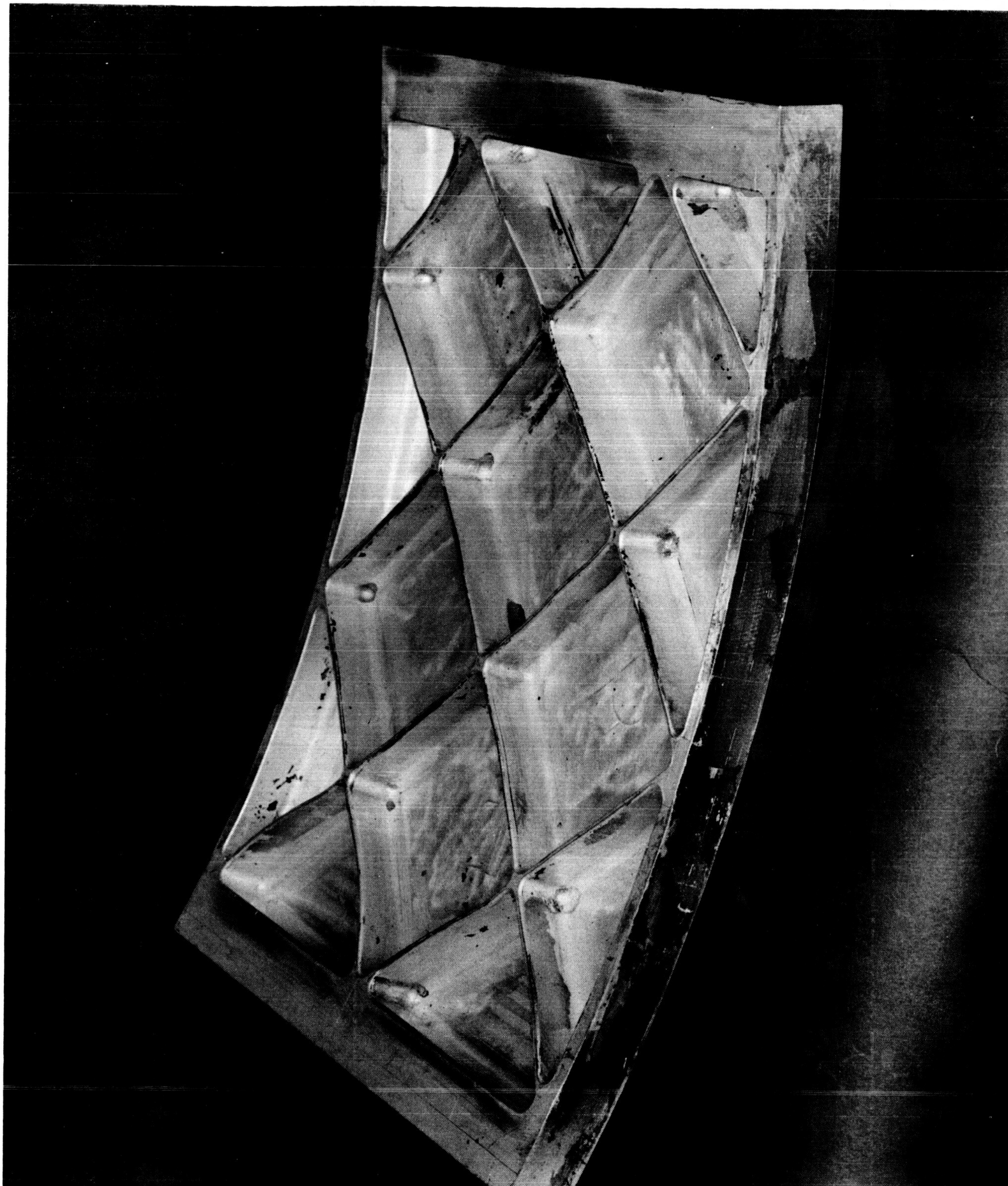


Photo 4. 45-degree Rib Pattern after forming.

5/ CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

Explosive forming of closed-rib plate would require an extensive feasibility and development program to establish techniques for individual shapes.

Experimental work on the forming of integrally stiffened aluminum panels by shot peening has been performed by Metal Improvement Company. The uniaxially ribbed plates ranged from thicknesses of 0.125-inch to 1.00-inch and were contoured to minimum radii of 10 inches and 1260 inches, respectively. An extensive development program would be necessary to determine feasibility and predictability of limits for forming closed-rib panels by this method.

Simultaneous age-forming and creep-forming methods are feasible for contouring closed-rib sections. This method is presently being developed.

Closed-rib shapes can be contoured to cylindrical shapes by standard press brake and roll-forming equipment. Hardened punch-and-die tooling is recommended for press-brake method.

In roll and brake forming, proper machine pressures and setup geometry must be determined by analysis to attain optimum forming. Failure caused by roll or brake pressures and resulting axial loads must be avoided.

Derived limits indicate the stretch wrap forming method will allow closed-rib panels to be formed to smaller radii than either roll- or brake-forming methods.

In stretch wrap forming, accurate load settings of the machine must be calculated to determine proper preload and set load to attain optimum forming.

The strain theory, as derived, appears to be the correct approach. This is due to the nonlinearity of the modulus of elasticity above the proportional limit of the material. This theory provides for a geometrical solution of forming predictability.

It is expected that good correlation of theory to practice in the forming of shapes with ribs parallel to curvature will result. It is evident that the buckling formula constant is conservative because of the effective support of the ribs with the use of filler material. This constant should be modified to attain closer correlations.

The derived formulas do not appear valid relative to shapes having elements canted from the plane of curvature. The theory, in this case, is not conservative due to the moment induced into elements from the axial force components.

The derived limits for roll, press, and stretch wrap forming are presented in Figures 4 through 18 for each of the alloys included in the present study.

The derived charts are not valid to predict minimum radii of compound contoured panels. The charts will provide radii that cannot be achieved because the correct curve would be shifted to predict slightly larger minimum radii.

5.2 RECOMMENDATIONS

It is recommended that a component of both the 45-degree and 90-degree rib pattern be selected and stretch-wrap formed to the predicted minimum limits as determined from the developed procedures. These panels would be photo-gridded so that strain measurements can be made to determine the extent of correlation between actual and theoretical values. An analysis of the results would be made and used to confirm the predicted limits and to modify or revise the derived formulae to accommodate those variables exerting a significant effect which have not been accounted for in the present analysis. These would be the determination of the following items:

(a) Accurate buckling constants for elements on an elastic foundation (ribs supported by filler material).

(b) Limit buckling strains of ribs canted to the direction of curvature. This includes analysis of moments and axial loads induced by forming.

Tooling requirements would consist of the following:

(a) A kirksite die cast with appropriate lightening holes and hold-down lugs which would be machined to a known configuration.

(b) A set of stretch jaws which will have the capacity to accept material thickness as required by the selected sections.

The results of this program indicate that analytical determination of the following items should be accomplished.

(a) Predictability of high energy forming methods.

(b) Predictability of the shot peen forming method.

(c) Effect of compound contours on the minimum radii derived for single curvature.

5.3 ACKNOWLEDGMENTS

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Kaiser Aluminum & Chemical Corporation
Lockheed Aircraft Corporation
Hufford Machine Works, Inc.
Metal Improvement Company

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